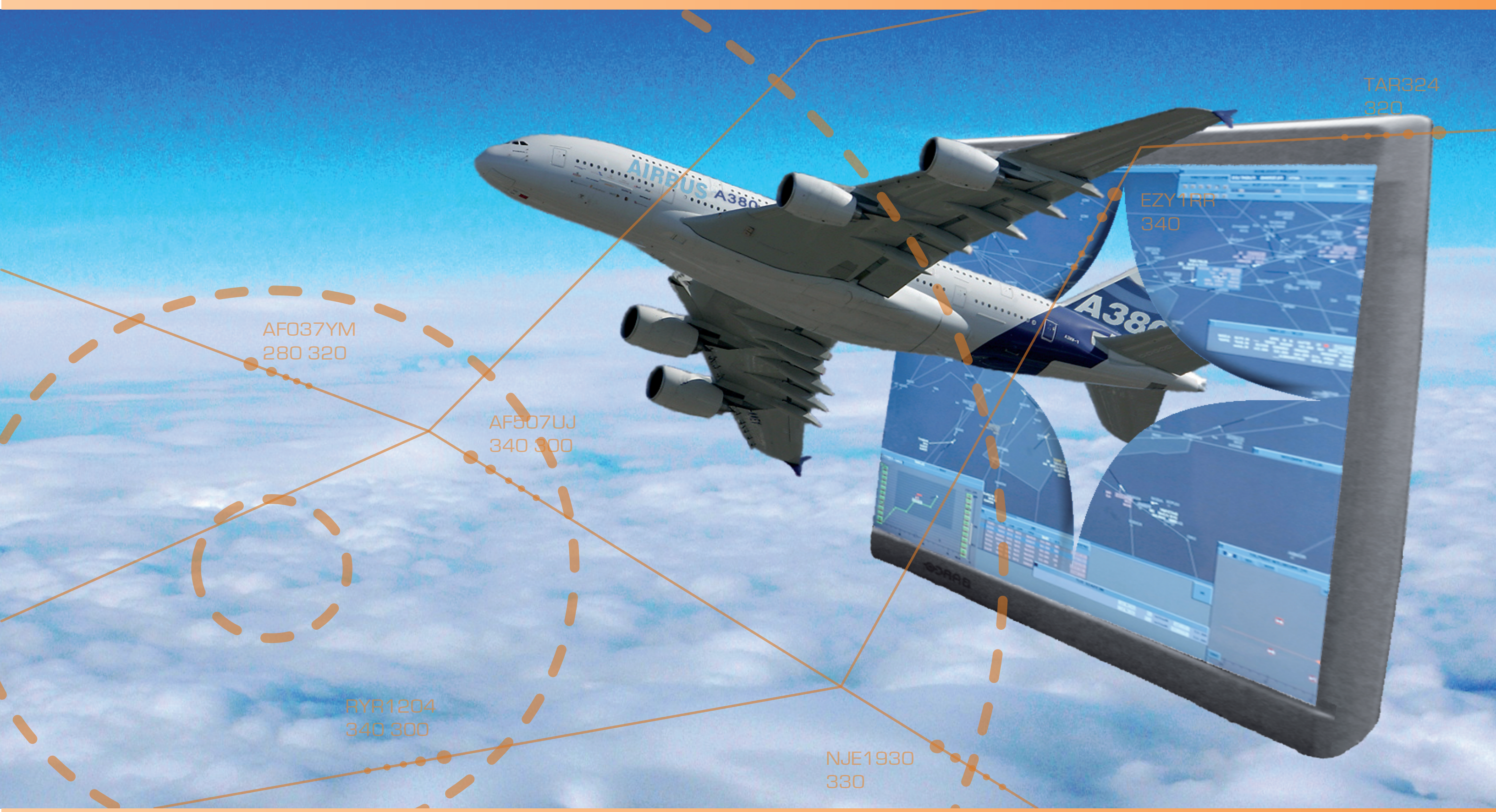
EUROCONTROL Experimental Centre

Brétigny sur Orge - France

4th - 6th December 2007

6th EUROCONTROL Innovative Research Workshop & Exhibition



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Estimation of En-Route Aircraft Emissions with Remote Sensing Tools (EMSAiTed Project): a Viability Study.

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***Abstract*— Here we present the results of the viability study conducted on the use of remote sensing tools for the estimation of the air traffic emissions produced during the en-route segment of flight in the UT/LS region (8000-12000 m).**

Among other important pollutant agents as CO_2 and H_2O constituting the bulk of the aircraft's plume, finally, NO_2 has been considered by the project as the gas tracer to be studied with the highest possibilities for success. For this reason a large amount of the project's effort has been dedicated to the in-depth analysis of the current technical potentials of the orbital sensors designed for the research and characterization of the atmosphere, with special attention for those instruments capable of measuring the concentrations of NO_2 in the atmospheric layers located in the proximity of the Tropopause.

The Canary Islands Corridor has been selected, for its high density and stable traffic conditions, to conduct an emissions' calculation exercise for an ideal emissions scenario obtained starting from real traffic and operational data.

The results obtained have allowed the comparison of the above theoretical situation with the detection limits of current space sensors as SCIAMACHY and OMI, and thus extract conclusions on the real measuring capabilities of these instruments. A complete analysis of the NO_2 data produced in the last years by the sensors quoted above has also been carried out. Global level results as well as those obtained in a specific manner over areas such as the Canary Islands' Corridor and the North Atlantic have also been considered by this study.

The general conclusions of the viability study are not optimistic, as we consider practically impossible, with the current technological level of the space sensors, to be able to detect air traffic emissions. Nevertheless, from all the results obtained further prospects and alternatives to improve this possibility in the future have been proposed.

***Index Terms*—Aviation, Emissions, Satellite, Viability.**

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I. INTRODUCTION

AVIATION as an industry and ATM in particular, as part of this industry are under a tough push and pull: on one side the increasing demand for traffic on the other the growing public environmental concerns.

Commercial aviation is a key worldwide activity subject to very stringent control measures, mostly the ones related to safety and security. The technological improvements introduced in the aircraft in the last years have not only been addressing the improvement of the above areas, they have also looked and delivered improvements in the efficiency of the engines. But, although, it is true that flight efficiency is proceeding steadily at a pace of 2% a year, in the long-term the aviation industry will see a decoupling of the efforts, gained by technology, to the increase in traffic. Naturally the increase in the net volume of pollutant emissions from this sector is already growing.

The IPCC, as well as other bodies, have been warning of the environmental effects that air traffic emissions could generate, especially for their influence, in the mid to long-term, on climate change [1].

The concern is fundamentally based on results obtained through various research projects which started at the beginning of the 90's [2], [3], [4], [5]. These scientific researches have widely documented the behaviour of the atmosphere around the Tropopause, which corresponds to the cruising segment of flight. As a result of this great research effort, knowledge on the emissions produced by aircraft, together with their influence on the chemical equilibrium of the atmospheric region and their possible implications, in relation to a possible climate change induced by anthropogenic emissions, has greatly improved [6], [7].

All this knowledge has been achieved through research programs limited in time, so the documentation of these issues have no continuity in time. On the other hand, the key problem consists in limiting and monitoring the real aircraft emissions produced, unfortunately, this is still a pending issue.

It is true that important efforts have been dedicated to achieve a theoretical quantification of the fuel burn due to commercial air traffic as well as the quantification of atmospheric emissions generated by air traffic and the results can be considered as quite good [8], [9], [10], [11]. But the quality of the results greatly depends on the quality of the data supplied by the aircraft manufacturers with the inherent difficulty in obtaining an authentic guaranteed validation of the emission indices used.

II. Motivation of the Project

A. Review Stage

The growth experienced by the air transport at a global level in the last years has been translated finally in an increase in the emissions of atmospheric polluting agents, which goes against the desirable tendency of reducing the global level of emissions. On the other hand and a particular characteristic of the sector, the greater part of the same emissions actually takes place around of the Tropopause, that is to say, in those layers of the atmosphere whose physical-chemical evolution in the mid-term is uncertain and reason for serious scientific concern. Whatsoever and unlike other productive sectors, in aviation not many means and tools exist to monitor and control real emissions. These types of deficiencies were those that inspired the EMSaiTed project.

The four main reasons for which the project was designed follow:

1) At present no methodology is available to document in a systematic way the real emissions coming from commercial aviation.

2) The only open road to consider the produced emissions in this sector is through modeling from emission factors; nevertheless, a certain lack of confidence exists regarding the reliability of the theoretical results that these tools offer.

3). Looking towards a possible future scenario in which the civil aviation will enter the CO_2 market, it would be very advisable, from the management point of view, to have systems that provide direct and reliable information on these emissions.

4) For environmental reasons, it is extremely advisable to be able to follow the future real evolution of these types of emissions and for that precise purpose to design new methodologies whose management was outside the aviation sector.

5) Connect the aviation sector to other areas of research looking for synergies as well as for cross border innovation.

This was the strategic framework in which the EMSaiTed project was considered, whose general mission has been to evaluate the viability of the use of remote sensing from space as a future tool for the direct quantification of air traffic emissions on the en-route flight segment.

III. Methodology

The viability analysis was developed following a methodology whose steps are hereafter described:

1st) Bibliographical Review

The objective of this phase has consisted in the accomplishment of a retrospective analysis of the knowledge and the experience accumulated in the different international projects carried out since the beginning of the 90's about air traffic emissions produced in different corridors, their atmospheric impact and the availability of related information, obtained through space remote sensing.

The compiled information has been classified, paying particular attention to three fundamental aspects:

- The chemical composition of the air in the corridors and their areas of influence;
- The space sensors designed for the measurement of atmospheric components and, specially, the results offered by tele-detection from space on tracer gases in the Upper Troposphere and the Lower Stratosphere (UT/LS);
- The atmospheric dispersion/diffusion of aircraft exshaust plumes at cruise altitudes.

2nd) Selection of a sufficiently representative air traffic route/corridor with intense traffic, at a world wide level, in order to establish a scenario with well documented emissions, with which to be able to make a realistic study. Collection of the technical characteristics of the chosen corridor: its traffic demand and the types of airplanes in use.

3rd) Selection of concrete dates for the accomplishment of the study and modelling of the emissions generated in that corridor.

4th) Selection of suitable gaseous tracers

5th) Simulation of a maximum emissions' scenario: with representative data from the chosen corridor for the purpose of calculating the attainable maximum atmospheric concentrations for the selected tracers; calculation of these concentrations and the products that the satellites offer; Cross-check of the results of the simulation with the technical characteristics of the systems currently operative.

6th) Analysis of the satellite data available: at first on the global scene and secondly focusing the effort on the chosen corridor and the selected days, establishing the corresponding relation with the calculated emissions.

7th) General conclusions.

8th) Proposals and future prospects.

IV. Results and Discussion

A. Bibliographical analysis

In general, the results of the international projects carried out in the last years demonstrate that the measured concentrations of gaseous tracers in the studied air traffic corridors or their immediate surroundings display a strong variability in space and time and, therefore, great heterogeneity [12]. Among the multiple causes that explain this, are emphasized: the variability of the dispersive conditions; the seasonal dependency of the height of the Tropopause with latitude; and finally, the interference generated by the advection of pollutants from the surface to the higher troposphere [1].

One of the better studied air traffic corridors, up until the present day, has been the one crossing the North Atlantic (NAFC) and from the results obtained from the measurements taken in-situ, we can deduce that aircraft emissions' only have a small impact, on the corridor scale, in the concentration of NOx and the number of particles. The impact of CO_2, CO, H_2O and SO_2 emissions on the background concentrations of the corridor is hardly measurable [2]. In table I some data appears that allows the explanation of these experimental results.

TABLE 1

Pollutant	Emission Index (g / kg fuel)	Natural background at flight level (ppm)	Variability of natural background at flight level
CO_2	3150	370	Seasonal (and long term)
H_2O	1230	20-200	Very high
CO	n. a.	n. a.	Very low
SO_2	0.2 - 0.8	10^{-4}	Very low
NO_x	12 – 30	10^{-4}	Very low
VOC	n. a.	n. a.	Very low

In the table it can be observed that the emission of NOx (NO+ NO_2) per kg of fuel consumed by an airplane, is 100 to 200 times lower than CO_2's. As the natural background for this last one is 10^6 times higher than the first, the CO_2 emission only just influences its surroundings whereas the emissions of NOx do generate a remarkable contrast on the existing background. The situation for H_2O is similar to the one for CO_2.

Consequently, it can be confirmed that the NOx present in the UT/LS is influenced by air traffic. Due to the global spatial distribution of the air traffic, the concentration of NOx in the background for the layer 8-12km displays a clear latitudinal gradient in the Northern Hemisphere, with minimum values (20-40 pptv) near the Equator and maximums (200-300 pptv) in latitudes 50-60º N. Within the strong general variability, the detected concentrations are usually higher in the areas of influence of the air traffic corridors, as demonstrated by the data corresponding to the vertical profiles obtained in the different experiments made with in-situ measurements. These results show a nonhomogenous distribution of emission tracers within the layer of 8-12km with a significant increase in the NO_2 concentrations in those areas under the influence of air traffic [13].

As a consequence, it has been decided to consider nitrogen oxides, and more specifically NO_2, as the most suitable tracer, with which to carry out a viability study. It should be remembered that NOx transformation in the atmosphere follows different chemical routes. NO_2 is not only a primary pollutant emitted directly, but also one of the most important secondary compound produced in this NO_x evolution, and this is the reason of its great relevance.

The yield in the formation of NO_2 coming from the aircraft emissions is a function of the flight altitude. In the UT/LS the NO oxidation rate is lower than that which takes place in the low troposphere. The maximum ratio of NO_2/NOx that can be reached between 8-12 km usually does not surpass 40%, whereas in the lower layers this ratio can easily reach 75-80%. The reason for it is that the oxidation mechanisms of NO are strongly controlled by temperature. The fotoxidation of NO_2 also has an influence but to a lesser extent [14]

Experimental results have also shown that the dispersion of plumes produced by airplanes in cruising altitudes takes place in two phases. First it is governed by the turbulent movements generated in the air by the passage of the airplane (dispersion regime) and second it is controlled by purely atmospheric processes of diffusion and transport (diffusion regime). Depending on the atmospheric conditions the resulting plume will disperse through hundreds of meters or kilometres, taking up to a day in mixing itself homogenously with the air traffic corridor's background. However, speaking in general terms the dilution of an individual plume can take between 3 and 10 hours before reaching the concentration of the background.

On the other hand and depending on the conditions of atmospheric stratification and wind shears, the typical extension of a plume after 10 hrs of dispersion, can be of 200 m along the vertical dimension and 15 km along the horizontal one [2], [15].

B. *Current Remote Sensors*

In Table II a summary of the most important remote sensors dedicated to the atmospheric composition research is presented.

TABLE II
Main Space Remote Sensors devoted to atmospheric composition research

SATELLITE	ORBIT	SENSORS	ATMOSPHERIC CONSTITUENTS
ENVISAT	Near polar sun synchronous at 800 km.	SCIAMACHY	O_3, BrO, OClO, ClO, SO_2, H_2CO, NO_2, CO, CO_2, CH_4, H_2O, N_2O
		MIPAS	O_3, ClO, NO_2, CO, CH_4, H_2O, N_2O, NO, HNO_3, HNO_4, N_2O_5, $ClONO_2$, CFC's, HOCl, H_2O_2, C_2H_2, C_2H_6, OCS
		GOMOS	O_3, NO_2, NO_3, H_2O, O_2, aerosols.
		MERIS	H_2O, aerosols
ERS-2	Near polar sun synchronous at 800 km.	GOME	O_3, BrO, OClO, SO_2, H_2CO, NO_2
ACE	650 km, 74º inclination	FTS	H_2O, O_3, N_2O, CO, CH_4, NO, NO_2, HNO_3, HF, HCl, N_2O_5, $ClONO_2$, CCl_2F_2, CCl_3F, COF_2, CHF_2Cl, HDO, SF_6, OCS, HCN, CF_4, CH_3Cl, C_2H_2, C_2H_6, N_2, ClO
		MAESTRO	O_3, NO_2
AURA	Near polar, sun synchronous orbit at 705 km.	TES	H_2O, O_3, CO, CH_4, NO_2, HNO_3
		OMI	O_3, OClO, SO_2, NO_2, BrO, HCOH, aerosols
		MLS	O_3, CO, H_2O, N_2O, HNO_3, HOCl, OH, HCN, HCl, BrO, ClO, SO_2
		HIRDLS	O_3, H_2O, N_2O, HNO_3, $ClONO_2$, CH_4, NO_2, N_2O_5, CFC-11, CFC-12, aerosols
METOP	Near polar, sun synchronous orbit at 817 km.	GOME 2	O_3, OClO, NO_2, BrO, H_2O, O_2 , aerosols
		IASI	O_3, N_2O, CO, CH_4, aerosols.
ODIN	Near polar, sun synchronous orbit at 600 km.	OSIRIS	O_3, ClO, N_2O, HNO_3 CO, H_2O, NO_2
		SMR	O_3, N_2O, H_2O
TERRA	Near polar, sun synchronous orbit at 705 km.	MOPITT	CO, CH_4
		MODIS	H_2O, aerosols
UARS	585 km, 57º inclination	HALOE	O_3, H_2O, HCl, HF, CH_4, NO_2, NO, aerosols
AQUA	Near polar, sun synchronous orbit at 705 km.	AIRS	O_3, H_2O, CO, CO_2 CH_4, SO_2, aerosols
		MODIS	H_2O, aerosols
METEOR-3M	Near polar, sun synchronous orbit at 1000 km.	SAGE III	O_3, H_2O, OClO, NO_3, NO_2, aerosols

These systems have been specifically designed for obtaining the best yield possible in terms of resolution in space and time and detection limits, according to the state of art of technology.

Of the 21 sensors only 13 of them count with the resources necessary for the detection of NO_2. Their characteristics are presented in Table III.

TABLE III
Space Remote Sensors producing NO_2 data

Sensors	NO_2 product	Range
SCIAMACHY	Column	Tropospheric/Stratospheric
	Vertical profile	10-100 km
MIPAS	Vertical profile	15-50 km
GOMOS	Vertical profile	20-100 km
GOME	Column	Trop./Strat
FTS	Vertical profile	10-100 km
MAESTRO	Vertical profile	10-100 km
TES	Vertical profile	10-34 km
OMI	Column	Trop./Strat
HIRLS	Vertical profile	20-60 km
GOME 2	Column	Trop./Strat
OSIRIS	Vertical profile	10-48 km
HALOE	Vertical profile	15-130 km
SAGE III	Vertical profile	10-45 km

The products delivered by these sensors in relation to the presence of NO_2 in the atmosphere are of two types: column values or vertical concentration profiles.

The concept behind gaseous column refers to the number of molecules existing inside an imaginary atmospheric column with a base area of 1cm^2. The gaseous columns are calculated for any position (latitude-longitude) and are of two types:

- Total column, as in considering all the vertical extension of the atmosphere, and
- Tropospheric column, in which only the gaseous concentrations present in the vertically integrated troposphere are computed.

Although theoretically some systems allow obtaining vertical profiles with a lower limit beginning at 10 km, in reality the only ones which are considered as reliable belong to data obtained above 15km. Consequently, the information on the gases present at altitudes near the Tropopause can only be found in column data (total and/or Tropospheric).

For this specific situation SCIAMACHY and OMI are the sensors which offer the best technical performance in NO_2 measurement. Below in Table IV their main instrumental characteristics are presented.

TABLE IV
SCIAMACY and OMI Instrument specifications

	SCIAMACHY	OMI
Spectral range (nm)	240-1750 ; 1940-2040 ; 2265-2380	350-500
Temporal coverage	Global / 6 days	Global / 1 day
Horizontal resolution (km x km)	30 (along track) x 60 (across track)	26 (along track) x 48 (across track)
Max. swathwidth (km)	960	2600
Viewing geometry	Nadir	Nadir
NO_2 product	Total Column	Total Column
Scientific product	Col Trop./Strat	Col Trop./Strat
Detection limits col Trop/Strat (molecules cm^{-2})	2 10^{14} / 2 10^{14}	2 10^{14} / 2 10^{14}

The total columns are the only official products of the European Space Agency (ESA), whereas the Tropospheric and stratospheric columns are scientific products generated by other sources (e.g. the Univ. Bremen; KNMI/IASB/ESA; KNMI/NASA/NIVR; DLR).

The Tropospheric columns of NO_2 are always obtained starting off by calculating stratospheric columns from the measured total columns. The calculation of the stratospheric component can be made by following different procedures. The Reference Method Sector (RSM, IUP Bremen) is the simplest and consists of using the value of the measured total column on the sector of the Pacific Ocean as a Tropospheric clean background value and to assume that the stratospheric NO_2 is zonally homogeneous. The difference between the measurement of total column and the value determined in the same day in the corresponding reference sector (same latitude) is interpreted as a value of Tropospheric column [16], [17].

Another procedure to obtain the stratospheric component from the total column of NO_2 consists of determining its contribution through the use of models (Chemistry Transport Model) that include stratospheric chemistry and temperature and wind fields. In this approach the stratospheric zonal variability is taken into account by the calculation. The stratospheric NO_2 distribution is employed to derive the Tropospheric column by subtracting the modelled column from the measured one (KNMI/IASB/ESA; KNMI/NASA/NIVR; DLR) [18], [19], [20], [21].

As a consequence of these assumed hypotheses, used by the calculation procedures, the Tropospheric NO_2 column data obtained could have associated a considerable level of uncertainty. As an example, Fig. 1 shows the differences between the stratospheric vertical NO_2 column (SVC) obtained during 2003 and 2004 in two World Meteorological Organisation's (WMO) ground based stations: Izaña (Canary islands) and Mauna Loa (Hawai) with similar latitudes (only 8º of difference) [22].

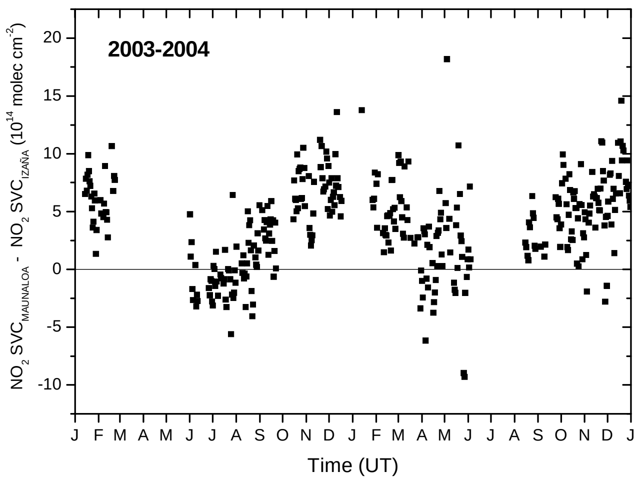

Fig. 1. Differences between NO2 Stratospheric Vertical Column (SVC) measured during sunrise at Izaña and Mauna Loa stations for 2003 and 2004.

These results clearly show that assuming that stratospheric NO_2 is zonally homogeneous and extrapolating stratospheric column data obtained over Pacific Ocean sectors to other zones of similar latitude is not realistic. The differences between the measurements at both stations clearly show that this NO_2 stratospheric homogeneity does not exist.

C. *Results from the Canary Islands' Corridor*

As part of the viability study the selection of an ideal scenario with real traffic and real flight operations was performed. The selection of a corridor with a long on-route trajectory and high traffic frequency and with accessible data fell on the Canary Islands Corridor (Fig. 2, Fig. 3).

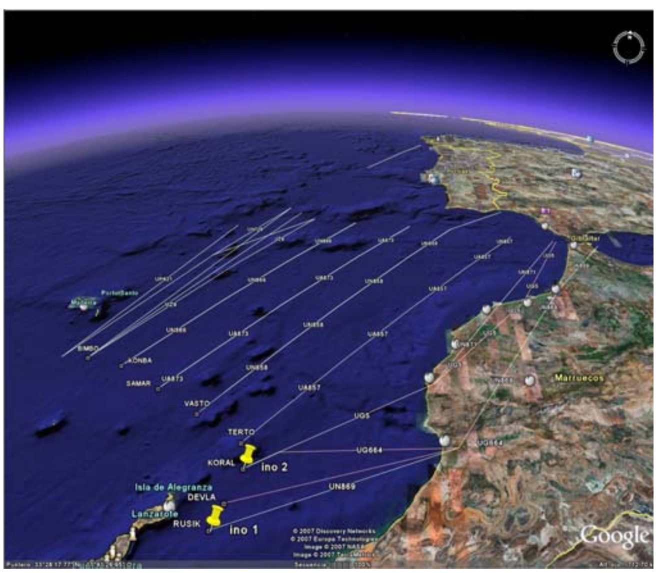

Fig. 2. The Canary Islands Corridor and its geographical location (Courtesy of Google Earth[TM])

The Madrid-Barcelona city link was also taken into account as candidate but finally put aside: among the drawbacks, the main being a route in evolution (climb/descent) i.e. the en-route phase was actually too small (~5 min.) compared with the Canary Islands' scenario; and the presence of traffic crossing in all directions along the route.

1) *The Canary Islands' scenario*

The Canary Islands Air Corridor connects the Spanish Peninsula and Europe to the Canary Islands [23].

It is composed of a system of four parallel routes Fig. 3 in the upper airspace linking the Iberian Peninsula and the Canary Islands. These extend through Casablanca FIR, which being in the AFI region, is included in the area for BRNAV implementation [24].

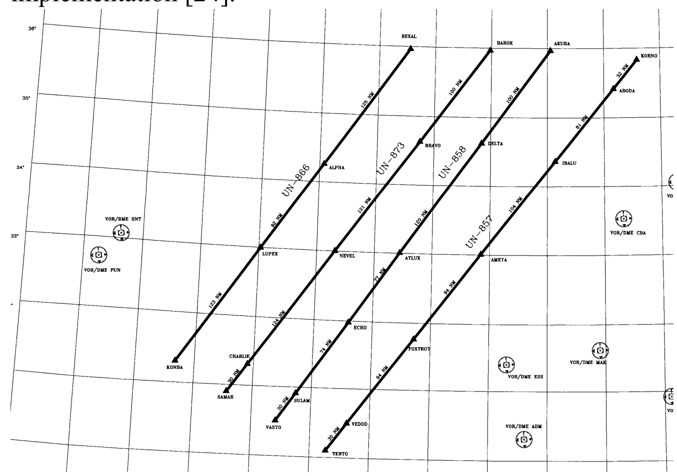

Fig. 3. Structure of the RNAV routes composing the Canary Islands Corridor [23]

The RNAV routes (UN866, UA/UN873, UN858 and UA/UN857) cross over coastal areas, with limited availability of conventional ground aids (VOR/DME). There is currently no full radar coverage in a large part of this zone. RVSM [23] is also applied to the volume of airspace between FL290 and FL410 inclusive in the Canarias UIR (AFI Region). This makes sure that the traffic is limited to a certain tunnel or a number of tunnels for each flight level see Fig. 4.

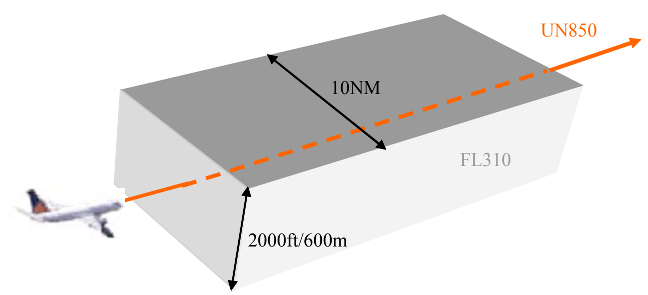

Fig. 4. Detail of the maximum navigational dispersion on one RVSM/BRNAV flight level along the Canary Islands corridor route.

The routes are not uniformly spaced, having a minimum separation of 43 nm (UN873-UN858), 53 nm (UN866-UN873) and 52 nm (UN858-UN857). On the other hand the distance between the routes is very important as it makes the routes independent of each other in terms of spatial overlapping of their emissions (atmospheric diffusion).

Operationally Canarias is in charge of handing over the traffic to Morocco at an established FL (required) and separated 20Nm for the same FL and the same velocity. All the traffic is already established apart from the one from Lanzarote where they climb due to their proximity. Once the traffic enters the Moroccan airspace no intervention is made until the traffic reches Portugal.

Routes such as the one going through VASTO, which are unidirectional, do not use all the flight levels available.

Air traffic will also be coming and going from the EUR/SAM corridor; logically they will have a preference on the FL compared to the departures from the Canary Islands.

2) Modelling with realistic data (demand, type of aircraft, route)

The route with the average highest annual (2006) traffic on the Canary Corridor is UN858 through VASTO. This is the route which presents the highest specific occupation, on the 23rd of December; in fact, it was flown by 225 aircraft (Fig. 5). Taking this date and its traffic as a reference, and taking into account the specific characteristics of the fleet, the total NOx emissions generated along the route thorough VASTO were calculated with the Advanced Emission Model III (AEM III), supplied by EUROCONTROL [8], [9].

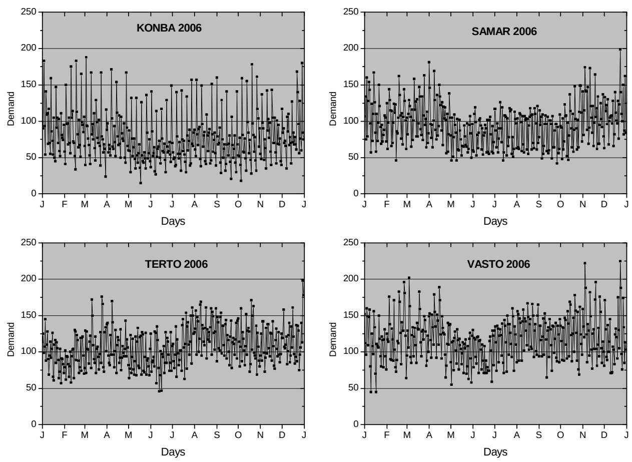

Fig. 5. Traffic demand along the four routes during the year 2006

3) Calculation of NOx Emissions along the UN-858 Route (with AEM III model)

The AEM III model was used to estimate the total amount of NOx for the chosen scenario.

Technical data:

- Date of traffic sample: 23/12/06
- Route: UN-858 Route through VASTO
- On route distance: 743,48 Km
- Nº flight: 225

Data required by the model:

- Air traffic data sample
- Flight data sample

The model gave us a value for the total NOx emissions of 5718,83 kg / day

D. *Simulation of the Canary corridor (with a situation of maximum accumulation).*

The emission data obtained from the AEM III, was used for estimating the maximum values of NO_2 columns that could be generated in an ideal atmospheric scenario. Several assumptions have been considered: constant velocity of each aircraft along the corridor; emissions coming from all the aircraft have been added up; absence of advection i.e. optimum dispersion conditions for its accumulation, and a maximum yield (40%) in the oxidisation of NO to NO_2 at these altitudes.

The column values have been calculated taking into account the area observed by each sensor. For this ideal case, the NO_2 column values obtained for the OMI and SCIAMACHY pixels were respectively the following:

- NO_2 column (SCIAMACHY): 0,67 10^{14} molec cm^{-2}

- NO_2 column (OMI): 0,83 10^{14} molec cm^{-2}

These results establish upper limits because they correspond to unreal conditions of atmospheric dispersion of the emissions since only the diffusion processes have been considered. On the other hand, the emissions from all the aircraft have been supposed to contribute to the values of the calculated column.

The values obtained for the NO_2 column in this exercise are far from the detection limits for both sensors (Table IV), i.e. it may be concluded that, even under those unrealistic conditions, the detection of the NO_2 columns due to air traffic emissions on the VASTO in the Canary Corridor could not theoretically be possible.

That conclusion can be extrapolated, in general terms, to other regions as in the case of the North Atlantic Tracks Region. As can be observed in figure 6 the fuel burn for both corridors are very similar. [10].

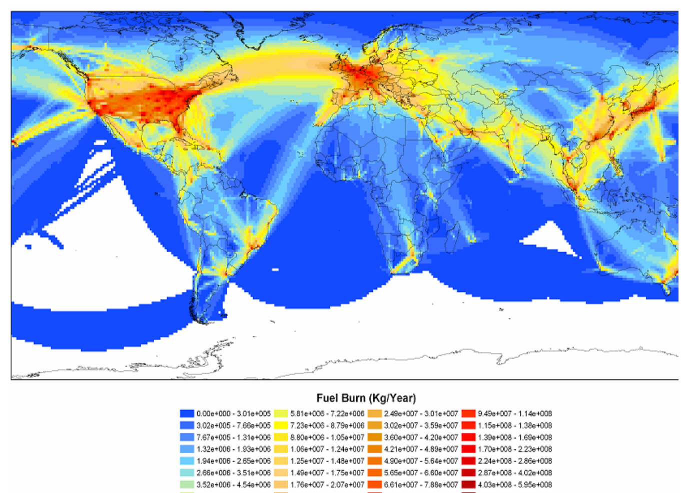

Fig. 6 Gridded Plot of Global Fuel Burn for 2000 with all altitudes Aggregated [40]

E. *SCIAMACHY and OMI data.*

Independently from these results a parallel and systematic research was carried out on the Tropospheric NO_2 columns supplied by SCIAMACHY and OMI [25], [26]. The analysis was carried out on a global scale and specifically for the areas of the Canary Islands corridor and the North Atlantic. In every case the results have been negative, with no correlation found between the recorded data and the emissions produced in the corridors. A few results from SCIAMACHY and OMI, presented hereafter, illustrate these conclusions.

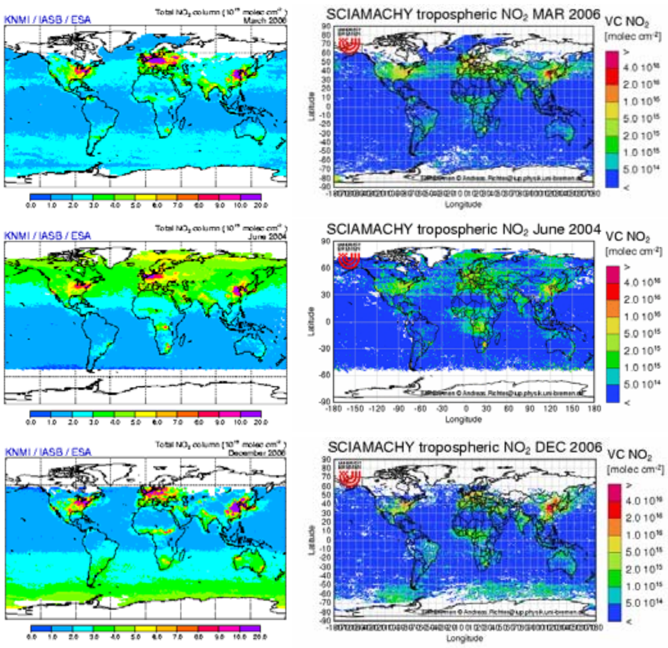

Fig. 7 Three examples of SCIAMACHY mean monthly values of total NO2 column (left) and Tropospheric NO_2 column (right) obtained by KNMI/IASB/ESA and Univ. of Bremen respectively.

In Fig. 7 two types of results obtained from the SCIAMACHY data are presented: three examples of monthly average NO_2 total columns (figures on the left) and the correspondent values of NO_2 Tropospheric column (on the right hand side) obtained by the Bremen University. These results highlight the influence that the total column values obtained with this sensor have on the results of the calculated Tropospheric column.

During the summer season (Northern Hemisphere) the maximum values of total columns are detected above 60N, as the June 2004 example, while during the winter season (Northern Hemisphere) the maximum are recorded below the 50S, as is the case for December 2006. This seasonal evolution corresponds to the changes in stratospheric NO_2 columns

Nevertheless, if the obtained Tropospheric columns for those situations are analyzed it can be observed the frequent existence of abnormally high values in the areas with maximum values of total column, that is to say, in regions far away from the possible source areas. These anomalous Tropospheric values occur as a result of the problems derived from the calculation of those columns and they do not respond to any real emission process or atmospheric physical-chemical dynamics. The difficulties arise when extracting the stratospheric and Tropospheric contributions from the total column in such a way that certain residual amounts of stratospheric NO_2 are finally computed like part of the Tropospheric columns.

At other times of the year the maximums of the total column are found at intermediate latitudes. In those conditions it is common to also find relatively high values of Tropospheric columns of NO_2 over the oceanic areas of those regions, as can be observed in the example corresponding to March 2006. The main cause is the calculation problem already mentioned, although in some cases the influence of processes as local emissions or long distance transport of pollutants could also play some role.

Tropospheric columns obtained by SCIAMACHY over the oceans, rarely surpass the level of $2 \cdot 10^{15}$ molec·cm^{-2} and this value could be considered either as a habitual uncertainty for these results or as a kind of effective detection limit. This means that the values of Tropospheric column that are superior to this level will be only slightly influenced by the calculation methodology.

The OMI sensor of the AURA satellite poses a different problem to the SCIAMACHY. Although the Tropospheric column results for NO_2, obtained with both sensors over the continental areas, usually tend to agree acceptably, discrepancies are frequent over the oceans. This is due to two fundamental reasons: the different spatial and temporal coverage of both instruments and the different methodologies used to obtain the Tropospheric data.

In Fig. 8 the average NO_2 Tropospheric columns determined from the OMI measurements for December 2006 and February 2007 are shown [26]. The results from December notably differ for certain zones from the ones obtained by SCIAMACHY (please refer to Fig 7above), which shows the complications and uncertainties associated with the generation of this product. In any case, the discrepant values are again around the order of $2 \cdot 10^{15}$ molec·cm^{-2}.

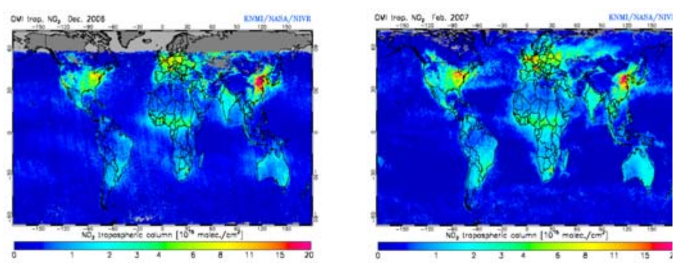

Fig. 8 Two examples of OMI mean monthly values of Tropospheric NO2 columns obtained by KNMI/NASA/NIVR.

In addition, OMI displays certain easily observable instrumental problems in the daily data, less visible in the monthly averages. For example, in the December data of Fig. 9 the appearance of "stripes" parallel to the trajectory of the orbits is perceived with certain clarity, this was due to an unexpected malfunction of its CCD detector [27]. As a result of this when generating the maps of column values anomalous levels can appear in different zones of the globe that are almost always shown in the form of stripes.

On the other hand, the nominal technical characteristics of OMI allow collecting with more frequency data on each zone, in addition to a better spacial resolution, for this reason OMI can detect certain processes with fewer difficulties than SCIAMACHY, such as for example, the emissions coming from maritime traffic.

In global terms, the emission of NOx due to this activity is considered to be in the order of 3 $Tg \cdot N \cdot yr^{-1}$, i.e. an amount 6-7 times higher than that produced by air traffic [28], [29], [30], [31]. Analyzing the NO_2 Tropospheric column data generated by OMI from June 2004 to the present, we can observe with certain regularity some systematic anomalies on some zones with intense maritime traffic (refer to February data in Fig. 8). For example, in this figure several commercial maritime routes could be partially guessed: between North America and Europe, the Red Sea, between the South from India to Indonesia, some to the east of Indonesia, etc. Nevertheless, next to these values of Tropospheric column attributable potentially to the maritime traffic, others of the same magnitude can also be observed appearing in areas away from these routes and unfortunately non attributable to any source or process, this fact actually disables a trustworthy allocation of the source of these values.

Independently of this evidence, we have proceeded to make a meticulous control of the data delivered by the satellites corresponding to the Canary Islands Corridor on the days in which the air traffic was especially high. In figure 9 the results obtained by OMI and SCIAMACHY for the 23 of December of 2006, the day used for the simulation of the emissions' scenario are shown as an example [26].

As can be observed, the daily average values of total column of NO_2obtained by OMI over the zone of the Corridor are similar to the registered ones over greater part of the northern half of Africa and oscillate between $2\text{-}3 \cdot 10^{15}$ $molec \cdot cm^{-2}$. However, the information corresponding to the Tropospheric column offered by OMI on the zone of interest displays lack of data (see Fig. 9). In the case of the SCIAMACHY data, the situation is even worse because the smaller daily spacial coverage of this sensor prevents it from having this information on the Canary Islands Corridor because Envisat is not passing through the vertical of the corridor.

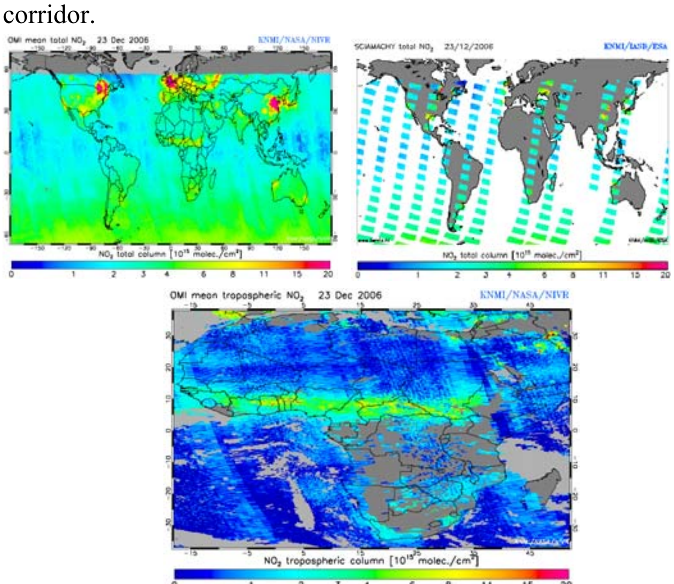

Fig. 9. Total and Tropospheric NO_2 columns: 23rd December 2006, from SCIAMACHY and OMI.

In any case, all the problems observed in the data from SCIAMACHY and OMI bring us to the conclusion that the uncertainty of the obtained values for Tropospheric column over the areas of the air traffic corridors of the Canary Islands and the North Atlantic is in the order of $2 \cdot 10^{15}$ $molec \cdot cm^{-2}$. This supposes a new argument that goes in the same direction as the results obtained from the simulation made with the emissions of the Canary Islands corridor.

Through this data, we can confirm that, considering the detection limits (nominal and effective) of the remote sensors currently in operation, the reliable detection of NO_2 due to the air traffic is not possible because those limits are undoubtedly higher than the necessary ones with which we would be able to distinguish, on the value of existing background NO_2, the value generated by the airplanes.

F. MIPAS.

Although Table III indicates that MIPAS only allows the detection of vertical profiles, these can be obtained by different measuring configurations modes. In fact this sensor includes a special measuring mode called "Aircraft Emission mode" (AE) specially designed for the exploration of the area covered by the North Atlantic Tracks, with the purpose of seeking to detect the contribution of the air traffic emissions to the existing concentrations of NO_2 in that atmospheric region [32].

The procedure is the following: when Envisat, the satellite carrier, crosses the NAFC the measuring unit is activated and the system, as well as its regular measurements along its orbit, carries out measurements on a lateral line of sight in which the North Atlantic corridor is seen along its axis, thus augmenting considerably its detection possibilities, since the explored optical path in this configuration is nearly tangent and overlaps the corridor along 500km, thus lowering the detection limit. Nevertheless, still no positive results have been obtained.

However, although with this way of measurement, the recovery of positive results in this corridor would be theoretically possible, the analyses made until now of the available data has not been satisfactory. The main reason being: the existing adverse atmospheric conditions in the NAFC during the accomplishment of the measurements.

The influence, by adverse atmosphere, on the results has been doubly negative: on the one hand, the massive cloud presence in that area strongly hindered the recovery of data from the radiative background and, on the other hand, the existing winds facilitated the atmospheric scattering of the emissions, which reduced the final concentrations reached [33].

V. CONCLUSIONS

From the emission factors associated to air traffic for the different gases and their background concentrations in the upper troposphere/lower stratosphere, the NO_2 has been considered as the suitable tracer for the accomplishment of this viability study. Aircraft emissions' produce very significant increases in the concentration of this gas in the corridors, thus opening the possibility for it to be distinguished from the background levels.

The simulation made with the Canary Islands corridor from real traffic data and the computed emissions with AEM III, has allowed the estimation of the attainable NO_2 columns' superior limits, attributable to the emissions produced in that corridor. The values obtained in this exercise are obviously greater than those that really take place since in these calculations only the processes of atmospheric diffusion have been considered. That is to say, that the dispersive effects due to the real movement of the air masses have not been considered.

However, the results of these theoretically maximum NO_2 columns can be extrapolated to other corridors whose traffic (fuel consumption) is of the same order of magnitude as that of the VASTO route of the Canary Islands corridor. For example, any one of the routes contained in the NAFC would enter this category. However, as the accumulation of the considered pollutants in this simulation is hardly ever produced in real dispersive conditions, the columns of NO_2 generated in any corridor will clearly be smaller than those calculated. Definitely, atmospheric dynamics will always play a determining role in the possible detection of these emissions.

From the simulation results we may conclude that with the space remote sensing technologies available at this time it is not possible to obtain data on emissions produced by air traffic. The main reason is that the NO_2 detection limits of the sensors in operation are too high for the concentrations generated by the air traffic emissions. In addition, the calculation procedures that are used in obtaining both the NO_2 stratospheric and Tropospheric columns, introduce elevated levels of error for these products. This actually prevents the reliable identification of Tropospheric vertical columns with values inferior to $2\text{-}3{\cdot}10^{15}$ molec·cm^{-2}, that is to say, again values very superior to the theoretically attributable ones for air traffic emissions.

VI. Future Prospects

Next a small analysis is presented on the possibilities considered viable for remote sensing from space to be used in the future for the measurement of air traffic emissions.

A. *Passive Remote Sensing in use:*

Theoretically the function implemented in the MIPAS instrument of Envisat for the measurement of NO_2 throughout the NAFC, could give some positive results in cases of sufficient accumulation of polluting agents.

Its mode of sideway measurement is currently the only attempt at the moment implemented and with certain options to be able to detect gases related to air traffic emissions. However, this concrete system could only be operative in corridors whose direction was almost perpendicular to the orbit, as in the case of the NAFC, and whose level of emissions was similar. In other conditions the system, neither would it have the theoretical possibility of success.

B. *Future Passive Remote Sensing*

In order for the passive systems to be used for this purpose certain objectives need to be achieved:

- Reduction in the detection limits (e.g. NO_2);
- Improvement of the space and time resolution, starting, for example, by the employment of geostationary satellite systems (GEO) instead of low orbiting ones (LEO). The strategic change is already taking place in the near future aerospace programs, which foresee the inclusion of GEO systems. The European initiative GMES (Global Monitoring for Environment and Security), for example, foresees the development of five satellites (Sentinel1-5), in particular Sentinel-4, is a geostationary observation system aimed at the chemical characterisation of the atmosphere. At the same time, EUMETSAT and ESA are currently defining the requirements for future missions (Meteosat Third Generation), also geostationary, with applications ranging from meteorological to atmospheric chemistry applications [34][35][36][37]. These systems are foreseen to deliver total column data for NO_2 with time/space resolutions of one hour and 10 km respectively. These improvements compared to LEOs, will help the detection possibilities' of emissions due to air traffic, always the detection limits for NO_2 and the necessary algorithms for the extraction of Tropospheric columns are improved as well.

NOAA and NASA on their side are working on the prescriptions of the GOES-R (Geostationary Operational Environmental Satellites) series, with the aim at obtaining products related to air quality. To achieve this objective it follows that the time/space resolution of the current systems must be improved [38].

- Possible implementation of functions/capabilities focused specifically on the measurement of aircraft emissions. Systems could be built with the intention to explore specific corridors, or procedures could be designed specifically for the exploration of special events, when detected, such as during contrail formation. In these cases, the dispersion is minimum and contrails allow determining with great exactitude the coordinates of the trajectories. For example, with geostationary systems an automatic detection of these events could serve to focus all the detection capacity of the sensors on those zones of interest during the time needed: until the adequate signal to noise ratio was reached for the NO_2 measurements.

C. *Future Active Remote Sensing*

The potential for active remote sensing for the determination of gaseous compounds is superior to the ones encountered by the passive systems; nevertheless, the technical difficulties are even greater. The ideal situation would be a DIAL (Differential Absorption LIDAR) system able to detect specific compounds in the atmosphere by means of using laser technology. At present this system is widely used by ground based observations, nevertheless there is no experience on the implementation of this in space.

In May 2006 ESA selected 6 missions as new candidates to be part of the family of Earth Explorers for to the Living

Planet program [39]. One of those 6 possible missions is called A-Scope and is designed for the measurement of CO2 from the use of a DIAL system whose design is in exploratory phase. If this mission is finally sent and successful, surely it will open the way to future active systems for the measurement from space of atmospheric components, and with it the opportunity to detect air traffic emissions.

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EUROCONTROL

ABCD: Aircraft Based Concept Developments (November 2007)

Roger Argilés Solsona, Stephanie Stoltz, Marc Houalla, Diana-Luz Laborde

***Abstract* —Air transport punctuality is the "end product" of a complex interrelated chain of operational and strategic processes carried out by different stakeholders (aircraft operators, airports, air navigation providers, etc.) during different time phases and at different levels up to the day of operations. Punctuality is affected by the lack of predictability of operations in the scheduling phases and by the variability of operational performance on the day of operations. Furthermore, part of the unpredictability of a given flight derives from the lack of information about the status of the previous flights using the same aircraft.**

Aircraft-Based Concept Developments (ABCD) proposes to improve flight predictability by linking flight plans using the same aircraft through the aircraft registration information.

The present document presents ABCD concept definition and potential implementation. It shows how, thanks to this aircraft registration linkage, ABCD would allow a better anticipation of flight delays resulting in a decrease of global ATFM delays and thus, in a better use of the ATM available capacity. In this way, ABCD intends to constitute a true evolutionary step forward in the improvement of predictability and efficiency of the ATM operations.

The paper also presents airlines' positive feedback on ABCD concept and introduces next steps to prove the cost effectiveness and the feasibility of its implementation.

***Index Terms* — Airlines, ATFM, CFMU, CTOT, Delay, EOBT, FPL, Slot Assignment.**

I. Introduction

NOWADAYS, air transport stakeholders (airlines, ANSPs, CFMU, airports) have established several processes, which aim at maximizing the use of available capacity while ensuring safety and a fair, transparent and non-discriminatory use of existing facilities. The two main processes are airport and ATFM slots allocations, since they deal with the main bottlenecks of the system: airports and airspace.

Each of these two processes has its own logic [1]: airport slot allocation process ensures the balancing between airlines' strategic demand and airports' capacity, while the ATFM slot allocation process introduces the operational flexibility required in order to react to more tactical perturbations. These processes are complementary and take place at different chronological phases: the airport slot allocation process is ensured during the strategic phase, several months before the day of operations; while the ATFM slot allocation process is performed during the day of operations, a few hours before real execution of flights.

The FPL (Flight Plan) management links both processes; through FPL aircraft operators transform allocated airport slots into EOBT (Estimated Off-Block Times) and collect all the relevant information about planned and actual flights. For flights within the European airspace, aircraft operators send to the CFMU a FPL message containing basic information about the flight in order to obtain clearance to over-flight, take off and/or landing at European airports. The aggregation of all FPLs, sent by airlines and handled by the CFMU, constitutes the "FPL database".

With this definition, the FPL database provides a picture of the overall aircraft traffic, which is flying and going to fly over Europe in the future. This database is regularly updated upon the reception of messages, sent essentially by airlines to the CFMU through IFPS, through CDM (Collaborative Decision Making) at some major European airports and through the real aircraft position provided by radars. The FPL database is composed of individual flight plans, which are not linked to each other.

In the same time, it has been determined that when a delay appears on a given flight, part of this delay propagates for the next flights using the same aircraft. In one of its previous studies [2], ADV systems has evaluated the impact of an ATFM delay on a daily itinerary on the Air France fleet by measuring its knock-on effect, which could be defined as the cumulative delay due to the propagation of the ATFM delay throughout the itinerary.

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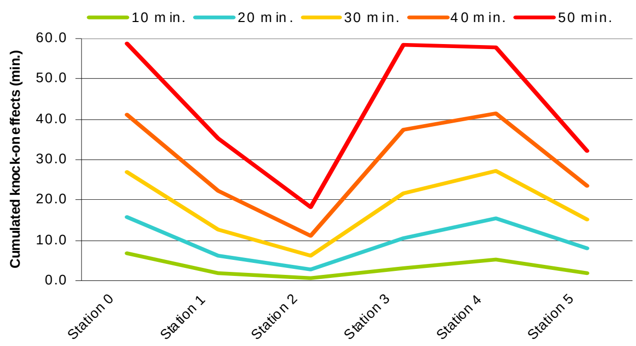

Fig. 1. Cumulated knock-on effects due to a single slot.

In the figure, the knock-on effects are shown for different legs of an aircraft's itinerary: station 0 corresponds to the first leg of the itinerary (i.e. first airport of departure), station 1 corresponds to the second airport of departure (first airport of arrival) and so on.

The overall result shows that knock-on effects are not a constant proportion of the initial ATFM delay. For instance, a 20-minute ATFM delay allocated at station 0 generates approximately 15 minutes in knock-on effects whereas a 50-minute ATFM delay at the same station produces nearly 60 minutes in knock-on effects. In the same way, a 50-minute ATFM delay occurrence at station 2 will generate less than 20 minutes in knock-on effects.

Thanks to the linkage of individual flight plans, it would be possible to provide more accurate predictions of the downstream legs of an aircraft itinerary, in particular when a flight suffers from perturbations (e.g. delays). Such accurate predictions are expected to lead to an optimized ATFM slot allocation process by allocating more efficiently the ATFM slots on an early up-to-date knowledge of the flight progress.

II. Methodology

Aircraft-Based Concept Developments (ABCD) explores the reorganisation of the flight plan management into a re-named "aircraft-based" management. ABCD is primarily based on the use of aircraft registration in order to establish a link between the individual flight plans.

The main objective of this paper is to show that this linkage constitutes an evolutionary step forward in the improvement of predictability and efficiency of the ATM operations. This demonstration has been broken down into three steps:

1) ABCD Concept description,
2) ABCD Airlines' feedback,
3) ABCD Quantitative benefits assessment.

A. ABCD Concept description

As an introduction to the future work, this chapter introduces the main assumptions and principles underlying the ABCD mode of operations, the description of the expected environment for its deployment, the overall view of the ABCD services and the description of some of the key information required by the ABCD concept.

ABCD concept could be implemented through several different strategies. This paper will introduce the two main implementation alternatives retained during the study:

-- Centralised Implementation by CFMU: the different FPLs belonging to several itinerary legs of the same aircraft are linked by the CFMU through the aircraft registration.

-- Local Implementation by airlines: the different FPLs belonging to several itinerary legs of the same aircraft are linked by each airline through the aircraft registration.

The operating principles of ABCD concept for each strategy will be illustrated through a real case of aircraft operations. This case was selected according to interviews held with airlines, which showed that airlines operations are frequently impacted by the knock-on effects of delays due to a single perturbation occurring at a given station of the aircraft's itinerary.

B. ABCD Airlines' feedback

ABCD implementation would require minor adjustments on current ATFM processes and airlines would need to process extra information (allocate aircrafts to flights, information about turn around times). It is therefore necessary to make sure that airlines would be interested in the implementation of ABCD concept and that the required information is available.

Thus, a number of interviews with airlines have been conducted during this study. The interviews were aimed at knowing airline's current delay management policies and procedures, assessing the availability of information required by ABCD and getting their feedback on ABCD concept.

C. ABCD Quantitative benefits assessment

Once it has been demonstrated through a real case study that thanks to ABCD implementation it would be possible to better anticipate delays, this chapter aims at showing that some benefits previously demonstrated through the real case can be validated through statistical analysis using data extracted from operational databases. In order to assess the benefits brought by an earlier delay anticipation, the relation between delay anticipation and ground slot allocation has been studied.

The analysis presented in the chapter demonstrates in two steps that the implementation of ABCD concept would decrease ATFM delay:

-- firstly, showing that the anticipation of delay communication (DLA message) to the CFMU reduces ATFM delay and,

-- secondly, showing that ABCD implementation would improve current delay anticipation communication (DLA messages).

III. ABCD Concept Description

Several ABCD implementation strategies have been studied. Each ABCD implementation would entail some adjustments on the current ATM processes. This chapter summarises two possible implementation strategies highlighting the different implications for the stakeholders and in terms of operating principles.

A. *Roles and Responsibilities*

Any ABCD implementation needs the participation of the two major stakeholders: CFMU and airlines. This chapter describes the different roles that could be assigned to CFMU and airlines depending on the implementation strategy.

Scenario I: Centralised Implementation by CFMU

In the first scenario, FPL linkage would be centralised within CFMU database, since the CFMU, in its role of central processor of the information, is well positioned to make the linkage between the various elements following the evolution of an aircraft's itinerary.

In this case, airlines would have to provide the CFMU with an "aircraft allocation schedule" containing aircraft registration number allocated to each flight, during the pre-tactical phase of slot allocation process (the day before the day of operations). Aircraft allocation notification should be flexible enough to allow modifications when an airline decides to modify the aircraft allocated to a given flight (e.g. aircraft swapping) at the last minute. In addition, airlines would also need to provide minimum turn around times and stop times at each airport of the aircraft itinerary.

By processing this information, the CFMU would be able to update the downstream flight plans and to propose new EOBTs to airlines whenever it would be necessary, i.e. when a delay occurring during one of the aircraft's itinerary legs can not be absorbed during the following ground stops.

The use of ABCD concept and functions would be optional for airlines.

The main advantage of this scenario lies in the fact that the information is gathered in an unique central point. However, this solution would need technical and juridical adjustments from the CFMU in order to process new information (aircraft allocation and turn around times) and to propose new EOBTs to airlines automatically.

Scenario II: Local Implementation by airlines

In this scenario, the linkage of flight plans would be processed in airlines' operations centres. Each airline would be proposed an "ABCD implementation toolkit" that would recalculate the EOBT request for downstream flights of an aircraft's itinerary when the flight experienced a delay significant enough to provoke reactionary delays. Airlines would then be alerted by the tool and would communicate to the CFMU the new requested EOBTs taking into account reactionary delays.

The tool would need the same additional information described in first scenario and, again, it would be proposed as an optional tool to airlines.

By choosing this implementation strategy, the CFMU would not be impacted. Therefore, the main advantage of this scenario is that CFMU would not need to modify its database management and processes.

B. *ABCD operating principles*

The principles and the usefulness of ABCD concept are described through a real aircraft operations case, which was selected according to interviews held with airlines and extracted from the flight plan repository database (ARCH) of the CFMU. This section presents the propagation of a flight delay and describes how the situation would have been handled differently with ABCD implementation. It illustrates the benefits provided by ABCD concept.

The example considered is an aircraft operating routes between Lyon and Zurich airports, eight times per day. An aircraft is allocated to four flights from Lyon to Zurich and to four flights from Zurich to Lyon. An ATFM regulation was implemented during the afternoon to protect an en-route sector.

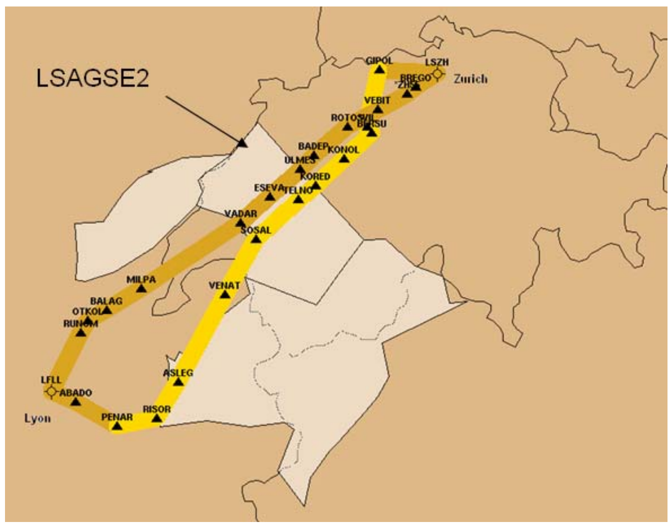

Fig. 2 Regulation LSAGSE2 situation.

The aircraft type is an ATR 42 identified by its registration. The example focuses on two successive flights, Zurich – Lyon and Lyon – Zurich, operated by this aircraft.

Both flights are subject to the same ATFM regulation issued to protect an en route sector LSAGSE2 (Switzerland) from over-delivery.

The Zurich – Lyon flight is identified by its airline call sign XX347. The flight departure (off-block) was initially scheduled at 16:05 but, due to the ATFM regulation, the departure was delayed to 17:01. Finally, the aircraft left the stand at 17:00.

Because of such allocated delay, the next flight of the aircraft's itinerary, the XX3478, was unable to meet its schedule. In addition, the same regulation applies on this second flight, so the initial scheduled off-block time at 17:45 was delayed to 18:16. However, such an allocation had been based on individual flight plans not linked together, thus generating an inconsistency: the XX3478 could not comply with a departure slot at 18:16 due to the initial delay allocated to XX3477 flight.

Indeed, in the present example, the scheduled stop time was very short (only 30’). This time is the minimum time necessary for the activities of handling, refuelling, boarding and deplaning of passenger for an ATR 42 aircraft. Therefore, a delay occurring during the XX3477 flight will be propagated to the next XX3478 flight.

Recorded data show that the XX3478 flight was effectively unable to respect the slot allocated on the basis of the initial flight plan at 18:16 and the time of departure was 18:44. Airport operations were impacted as the aircraft stayed at the airport during 44 minutes, instead of the 30 minutes scheduled turn around time.

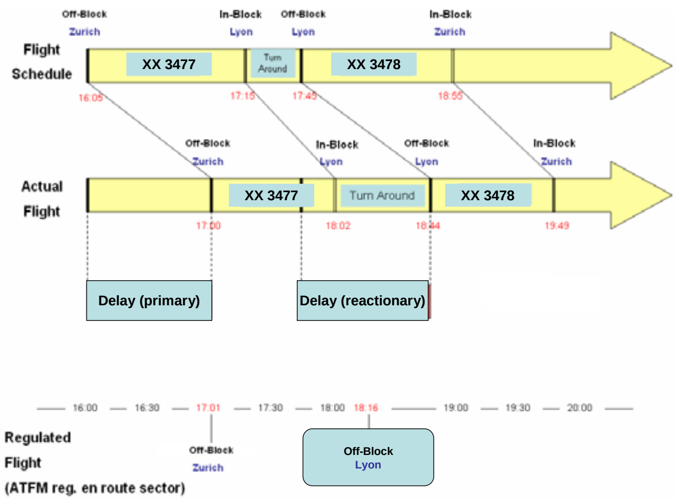

Fig. 3 Flights XX3477 and XX3488.

Moreover, ATFM slot allocation process was impacted by the fact that the two flights XX3477 and XX3478 were not linked together. Thus, the slot allocated to the XX3478 flight corresponding to a regulated calculated time over (CTO) at 20:01, could not be met because of the regulation applied on the previous XX3477 flight.

CFMU SLOT ALLOCATION LIST

Flight	Initial time over reference point	Regulated time over reference point
XX3478	19:30	20:01
YY910	19:30	20:03
ZZ1230	19:30	20:05

Actual Time Over XX3478 20:32

Fig. 4 Regulation slot allocation list.

The following section presents how slot allocation mechanism could have been improved applying ABCD principles and describes what would have happened in both implementation scenarios presented.

Scenario I: Centralised Implementation by CFMU

If ABCD concept had been implemented, slot allocation processes would have been different. First of all, the airline would have sent the required information to CFMU: an aircraft allocation schedule the day before the day of operations allowing the linkage of flights plans and information on turn around times.

Thus, the CFMU system would have known that the aircraft needed to stop at least 30 minutes at Lyon airport and would have linked the FPLs corresponding to the XX3477 and XX3478 flights, by using the aircraft registration number. Therefore, the CFMU could have evaluated the delay propagation effects for the next legs of the delay occurring at Zurich airport.

Within the CFMU FPL database, XX3478 flight profile would have been updated according to the up-to-date information concerning the previous XX3477 flight, which would have optimised the overall slot allocation process.

Because of the linkage of the FPLs, the system would have known that XX3478 was unable to comply with a slot allocated on the basis of an individual flight plan at 20:01. This would have been detected in advance contributing to the optimisation of the process. In the example, the 20:01 slot could have been allocated to another flight, the YY910, which hence would have benefited from an improved slot. In turns, this would have freed a slot for the next ZZ1230 flight. Then, the overall delay generated by this very regulation would have been reduced. Without ABCD, the analysis performed for this real-case study shows that the 20:01 slot was lost.

Apart from the mentioned improvement in slot allocation process, ABCD implementation would also provide a more consistent on-line information about aircraft status. The CFMU constantly processes up-to-date information messages issued by ANSPs that provide real-time position reports. As soon as the aircraft takes off, the system has the confirmation of the real delay of the aircraft. The actual departure time of XX3477 flight was 17:00.

The system would re-calculate the times at Lyon airport according to the latest information about XX3477 flight. So, it would provide more accurate estimates of the in-block XX3477 time and of the EOBT corresponding to the next XX3478 flight.

Then, it would be possible to transmit the updates to all interested actors at Lyon airport which would benefit from more accurate and consistent information. Besides, the updates would also be transmitted more than one leg ahead of the aircraft itinerary if the following legs were also impacted.

In the presented example, accurate information could have been provided as soon as the aircraft had taken off from Zurich, i.e. about 70 minutes in advance for the turn around operations at Lyon. Thus updated information on the schedule at the following stage would be available 100 minutes (70’+30’) before the next stage, and so on.

Scenario II: Local Implementation by airlines

This scenario presents very similar characteristics to the centralised one. The main difference lies in the fact that the detection of delay propagation is made by airlines' operation centres instead of by CFMU.

More precisely, in this scenario, contrary to what happens in the centralised scenario, flight plans' information remains the same as nowadays.

Furthermore, instead of sending an aircraft allocation schedule to CFMU, the necessary ABCD information is an input to "ABCD implementation tool" deployed at each airline's operation centre.

Therefore, it is not the slot allocation system that detects the delay propagation effect but the ABCD implementation tool that consequently calculates new EOBT to request. Then airlines would have sent a DLA message to CFMU with the new EOBT requested for each of the downstream flights and the system would have proposed a new slot to XX3478 and the slot 20:01 would have been also saved.

It is considered that the new EOBT request is sent to CFMU when ABCD implementation tool detects a delay propagation effect. Hence, the system knows that one slot will not be used approximately at the same time as in the centralised implementation scenario.

IV. ABCD Airlines' Feedback

Interviews with airlines were performed during this study in order to obtain information on the operational framework of each airline and to get their feedback on ABCD concept.

Recognising that different airlines have different requirements and expectations, three different categories of airlines were considered. The first one corresponded to "flag-carriers" or "major airlines", whereas the second and third groups were respectively composed of "low-cost" airlines and regional airlines.

A. Availability of required extra information

In order to provide required input data to ABCD concept, all interviewed airlines stated that they would be able to send information about the assignation of individual aircrafts to flights, flight schedules and turn around times at airports, at least one day before the day of operations.

B. Delay management strategies

Major airlines have their own tools (ABCD-concept tools & decision-making tools) and policies helping them to decide the optimum moment to communicate a delay to the CFMU. Moreover, the use of hubs allows these airlines to swap aircrafts during the day of operations in order to recover from major delays and their management tools allow them to handle such complex operations.

Low cost and regional airlines have different strategies for delay management: some of them communicate delays at the very last moment (EOBT-10'), trying to recover the delay until the last minute in order to avoid passing at the queue of slot allocation list; while others communicate delays at the moment they appear. Low-cost and regional airlines state that ABCD implementation would be very useful for them in order to facilitate their delay management policies and optimize their slot allocation process.

C. Interest on ABCD concept

As a conclusion, low-cost and regional airlines would be interested by ABCD concept implementation as it allows a better anticipation of delay communication to CFMU (minimizing ATFM delay) and simplify the delay and the flight plan management.

Major airlines would not be directly interested by the implementation of this concept since they already have similar tools. However, these airlines would benefit from ABCD concept implementation as a result of the improvement in the use of the available ATFM capacity.

V. ABCD Quantitative Benefits Assessment

The analysis presented in this chapter focuses on ABCD impact on the most penalizing regulations: "Smoothing disruptions through ABCD concept". Therefore, the ground regulations provoking the highest ATFM delays were selected amongst the regulations issued in September 2006 in the ECAC area. Focusing on regulations imposing heavy ATFM delays seems a sensible approach as the corresponding delayed flights may have an impact on airlines operations as well as on CFMU since the higher the rate of unused slots, the higher the waste of capacity.

A. ABCD impact on ATFM delay

The shorter the anticipation in sending a DLA message, the higher the risk of being constrained with a high ATFM delay. This assumption relies on the fact that the earlier the CASA algorithm [3] is aware of the need to find a new slot for a given flight, the more chances it has to find a slot that fits airline's request.

A DLA message with information about the time of the new EOBT (Estimate Off Block Time) is sent to CFMU by airlines whenever a delay greater than 15 minutes is detected.

DLA messages containing EOBT are registered in CFMU system, which also records the exact time the delay message has been sent. The difference between the time the DLA message has been sent and the new EOBT is called "the delay anticipation". The delay anticipation concept illustrates how much in advance an airline communicated a delay to the CFMU. For this analysis, flights were grouped in delay anticipation windows of 20 minutes.

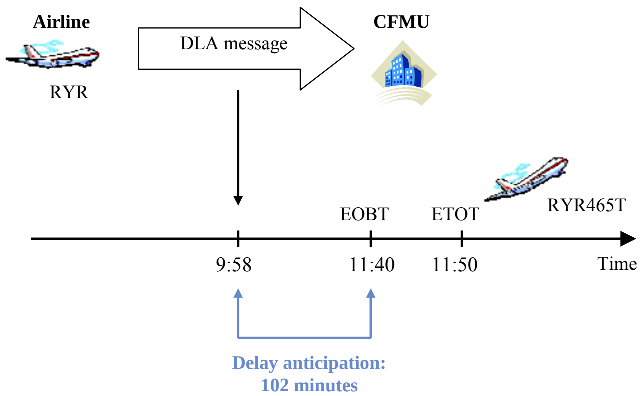

Fig. 5. Delay Anticipation Concept.

ATFM delay assigned to each flight is known from regulation reports. All the figures presented in this chapter only take into account delayed flights, meaning flights that have sent a DLA message, since the objective is to know the additional ATFM delay assigned to flights depending on the anticipation sending these DLA messages by airlines.

Delay anticipation analysis has been limited to 160 minutes before EOBT because CASA algorithm starts giving priorities to flights based on FIFO policy at EOBT-180' [4]. Hence, a DLA message sent before EOBT-160' is considered almost like a non delayed flight.

In order to be as comprehensive as possible and avoid biases in studying the relation between the delay anticipation and its associated ATFM delays, the analysis was segmented as follows:

- -- Regulation's typology (weather related regulations vs non-weather related regulations)
- -- Airline's typology (major airlines vs low cost and regional airlines)
- -- Regulation's geographical zone (by country)
- -- FPL messages (analyse foreseen impact of sending FPL message instead of DLA message)

This chapter presents the results concerning the most relevant segmentations.

Correlation between ATFM delay and DLA Anticipation for non-weather regulations.

The following figure shows the correlation between ATFM delay and DLA anticipation (split in 20 minutes time windows) for non-weather regulations.

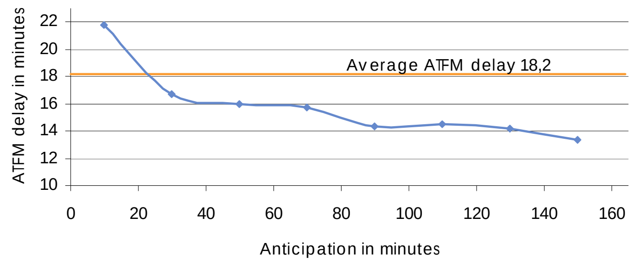

Fig. 6 ATFM delay vs DLA anticipation Non-Weather regulations

ATFM delay significantly decreases when delay anticipation increases:

- -- For small delay anticipations comprised between 0 and 40 minutes, ATFM delay decreases from 22 minutes to 16 minutes, meaning a 30% ATFM delay decrease.
- -- The trend is globally negative until the window [140; 160[and the curve seems to stabilize at an ATFM value around 14 minutes.
- -- The average ATFM delay imposed to flights that sent a DLA message (delayed flights) was 18 minutes.
- -- It is interesting to compare the average ATFM delay for flights that have sent a DLA message (delayed flights) with the average ATFM delay for flights that did not send any (flights on-time within the same regulations). The delay values for flights that did not send any DLA message was 14,1 minutes. The curve, shown in the figure 6, lies for high anticipation ranges around 14 minutes, which implies that the higher the delay anticipation, the closer their ATFM delay will be to the ATFM delay for flights that did not have any previous' delays. This figure would indicate that if an airline is capable to anticipate a delay more than 120 minutes before EOBT, the flight will not be imposed any supplementary ATFM delay. The underlying idea is that communicating a delay long time in advance is like not having any delay in terms of imposing supplementary ATFM delay.

It should be noted that the number of flights available to compute the average ATFM delays decreases when the anticipation increases. Figure 7 shows the sample size and its distribution split in 20 minutes time windows for non-weather regulations.

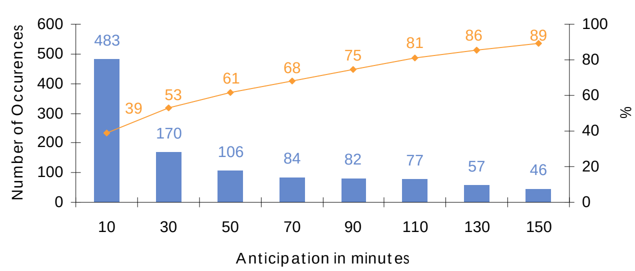

Fig. 7. Number of flights in each anticipation range

- -- 40% of the flights have sent their DLA message less than 20 minutes before EOBT.

-- More than half of the analysed sample (53%) is concentrated in anticipation between 0 and 40 minutes anticipation before EOBT.

-- Considering all flights that sent a DLA message, the average DLA message anticipation was 58 minutes.

The analysis presented in this section clearly shows that for non-weather related regulations the earlier the delay anticipation and communication to the CFMU, the lower the resulting ATFM delay values.

As the implementation of ABCD, thanks to the linkage of flight plan through aircraft identifications, will contribute to anticipate delays earlier and especially the delays of subsequent flights using the same aircraft, it could be stated that the use of ABCD will allow to decrease ATFM delays.

Correlation between ATFM delay and DLA Anticipation for weather regulations

The following figure shows the correlation between ATFM delay and DLA Anticipation (split in 20 minutes time windows) for weather regulations.

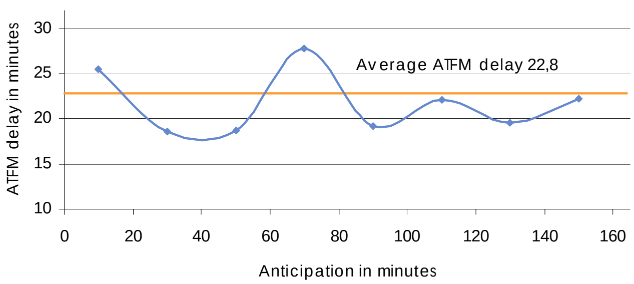

Fig. 8. ATFM delay vs DLA anticipation Weather regulations

There is not a significant general negative trend as it was observed for non-weather regulations The fact that the curve is not decreasing is the consequence of the uncertainty in weather regulations evaluation:

-- However, the average ATFM delay for flights with an anticipation inferior to 80 minutes is 23,4 minutes whereas flights that anticipated more than 80 minutes have in average 20,5 minutes of ATFM delay. Thus, the overall trend is negative.

-- It can be observed that the amplitude of the oscillations becomes lower for bigger delay anticipations.

The distribution of occurrences according to anticipation is presented in the Figure 9.

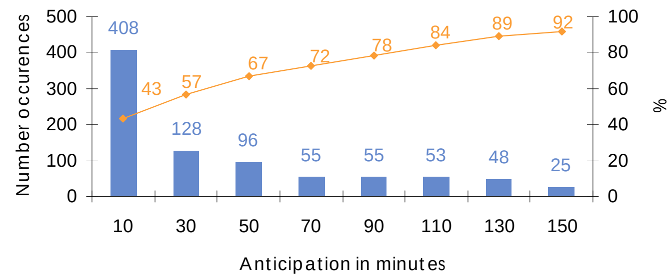

Fig. 9. Number of flights in each anticipation range weather regulations

This cumulative distribution for weather regulations has approximately the same shape as for non-weather regulations, though flights affected by weather regulations seem to anticipate a little bit less than for non weather regulations:

-- Most of flights anticipate between 0 and 20 minutes then the number of occurrences keeps decreasing as anticipation increases.

-- 57% of flights have anticipated less than 40 minutes for weather regulations, against 53% for non weather regulations.

The different impact of DLA anticipation for non-weather and weather regulations is probably due to the lack of predictability of weather-related regulations, which attenuate the positive impact achieved by increasing anticipation.

B. *ABCD impact on delay anticipation strategies*

ABCD implementation would enable the notification of delays from a leg of aircraft itinerary prior to the previous itinerary's leg (n-2). The analysis presented in this section aims at showing that airlines currently do not anticipate delays from a flight prior to previous flight.

The following diagram shows the different legs of an aircraft itinerary. Three legs have been represented: present flight (n), previous flight (n-1) and flight previous to previous flight (n-2).

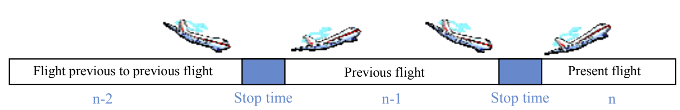

Fig. 10. Different legs of an aircraft's itinerary

Between two flights, airlines schedule a certain time called stop time that includes taxi time, turn around time and a certain margin that enables airlines to absorb delays.

When delays are bigger than the margin allowed by stop time there might be reactionary effects on the following legs of aircraft's itinerary. Therefore, the anticipation of a delay more than one stage ahead seems interesting in order to avoid disruptions at the subsequent stages and reduce ATFM delay in the following legs of aircraft itinerary.

ABCD would enable the communication of a delay that could not be absorbed by stop times more than one stage ahead. Thus, it would enable the notification of a delay for the present flight (n) from the previous flight of previous flight (leg n-2).

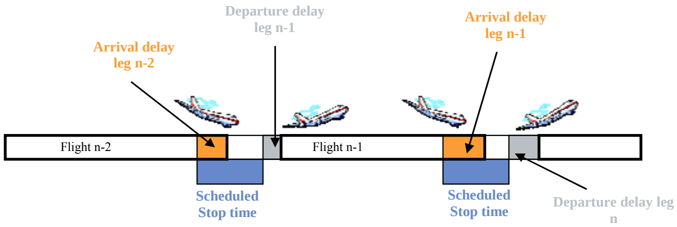

Fig. 11. Description of arrival and departure delays in aircraft itinerary

In order to determine whether flights currently anticipate delays more than one stage ahead, it is necessary to obtain information from previous flights' delays. To do so, flights were linked to the FPL of their previous flight. Previous flight arrival delay has been computed by making the difference between the actual time of arrival (ATA) and the estimated time of arrival (ETA) indicated in the previous flight plan.

More precisely, the analysis compares the different distributions of DLA communication anticipation among flights that had sent a DLA message (this means flights that were delayed) depending on whether their arrival delay at previous flight (leg n-1) was major or minor. Most flights with a major arrival delay were already delayed at their departure airport. This means that most of the flights, that had a major arrival delay, could have communicated their delay at the departure, with an anticipation, in average, of at least 120 minutes before the EOBT of the present flight .

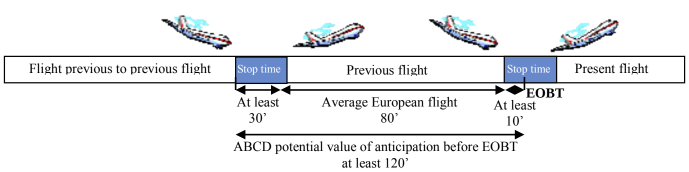

Fig. 12. Description of ABCD potential value of anticipation

If airlines communicate delays more than one stage ahead, it is expected that flights that had a major delay at previous' flight arrival would have communicated delays earlier than flights without delay on their previous flight.

For the aim of this analysis, flights were split between:

-- Previous flight (leg n-1) with major arrival delay: flights whose previous flights had an arrival delay greater than 30 minutes. This seems a sensible assumption taking into account average tight stop times scheduled by airlines, which are willing to minimize stop times to optimise their resources.

-- Previous flight (leg n-1) with minor delay: flights whose previous flight had an arrival delay between 0 (non-delayed) and 15 minutes.

For each group, flights were classified depending on the time at which airlines had sent the DLA

The following figure compares distributions for flights whose previous flight had major and minor delays.

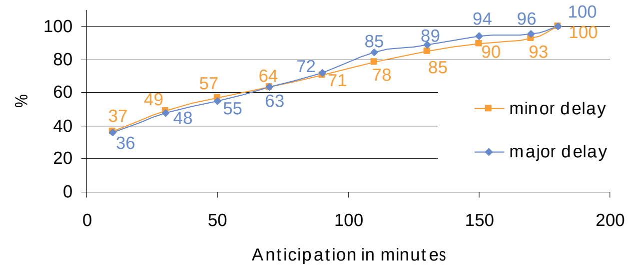

Fig. 13. Anticipation distribution of flights with previous flight delays

The distributions of flights with a major or minor delay at previous flight (leg n-1) arrival are quite the same:

-- Most of the flights anticipate less than 40 minutes.

-- Only 18% of flights (15% for major delay and 21% for minor delay) anticipate more than 120 minutes, which means that there are few flights that anticipate beyond the average "ABCD-potential" value of 120 minutes before EOBT.

If airlines did notify delays from the flight previous to previous flight (leg n-2), the proportion of DLA messages for flights with major delay (more than 30 minutes) would be greater at higher anticipation ranges than the one for flights with previous flight with minor delay (less than 15 minutes).

As it is not the case, this figure implies that very few airlines anticipate delays from more than one stage ahead of an aircraft itinerary, even though sometimes delay propagation may be known at stage n-2.

Through ABCD concept implementation, the propagation of a delay detected on a given flight and aircraft, could be analysed and its impact on subsequent flights using the same aircraft could be anticipated. For example, if a delay is detected on a given flight and if this delay could not be entirely absorbed during the following stop time stages, then ABCD would allow to anticipate delays more than one or two flight times before the flights departures. This time corresponds to at least an average from 80 to 140 minutes anticipation instead of 40 minutes as it is, nowadays, for more that one flight over two.

VI. Conclusion

It can be concluded through qualitative (interviews and analysed examples) and quantitative analyses, that ABCD implementation could bring tangible benefits to ATM stakeholders (airlines, CFMU, airports).

Quantitative analyses

Quantitative macroscopic analyses have proved that, whatever the information media used for the notification of a delay, the earlier the notification of the delay the lower the ATFM delay. They have also shown that airlines do not generally notify delays more than 20 to 40 minutes in advance. Thanks to the linkage of flight plans, allowed by the aircraft registration number, the ABCD concept would permit to better anticipate delays than nowadays. Delays would be notified earlier to the CFMU, which would result for the delayed flights into a decrease of their ATFM delay.

The reduction of ATFM delays would provide aircraft operators with a financial gain related to the cost of delay. For the CFMU and ATM stakeholders, ATFM delay reduction would mean a better use of the available capacity.

Thus, the implementation of an ABCD related tool would bring airlines financial gains and allow the CFMU a better use of the available capacity.

For low cost and regional airlines

The interviews have established that the implementation of ABCD provides these airlines with an efficient tool to recalculate automatically new CTOT for subsequent flights using the same aircraft as an initial delayed flight, once a delay on the initial flight has been detected and has found to be propagated throughout the subsequent flights. These airlines have stated that they were ready to provide the necessary data to feed such a tool and would be keen on the implementation of an ABCD-like tool.

For major or flag carrier airlines

In the case of major disruptions, these airlines have the ability and the resources of swapping aircraft for a given flight incurring too much delay. In some cases, they even have some tools similar to proposed ABCD concept implementation and they want to keep the ability of swapping aircraft readily. Thus, they are reluctant to use an ABCD tool when they have their own ABCD-like tool. Therefore, it is clear that the implementation of ABCD should not be imposed to all airlines.

VII. NEXT STEPS

The benefits brought by an ABCD tool have been proved through macroscopic analyses performed on CFMU files. Even if these analyses demonstrated benefits, they have not determined precisely the magnitude of these benefits. The only way to do so and thus to assess the benefits in a quantitative and accurate way, is to perform TACOT simulations on real traffic. These simulations will allow to measure to what extent, for a batch of given delayed flights linked with other flights by the use of a same aircraft, the earlier notification of the first delay would have resulted in a reduction of ATFM delays. As a matter of fact, the use of simulations is compulsory for a precise estimation of gains in delay, since the slot allocation process is a dynamic algorithm.

Simulations will also allow to measure the potential increase in capacity that could bring ABCD concept in case of restrictive regulations.

These simulations will also help to build a sturdy and realistic ABCD Benefits Model based on real quantitative values rather than on estimates or on interviews with airlines. In particular, as mentioned before, the simulations will allow a precise estimation of delay benefits which will be translated into financial gains.

The ABCD concept could be an efficient tool for low cost and regional airlines as well as for CRCO purposes. However, the implementation of such a tool could raise juridical issues, which should be analysed carefully in order to provide airlines with an interesting and efficient tool.

In the same way, the technical implementation of ABCD concept requires to specify how this concept would technically fit within existing ATM systems and especially the CFMU and CDM systems. In particular, the way information and data from existing systems could be used in order to implement this concept will be analyzed and a concrete implementation model will be proposed.

Finally, the benefits model combined with the proposed implementation model, from which could be derived associated costs, will allow the computation of a Cost Benefits Analysis.

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DICTIONARY OF ABREVIATIONS

ABCD	Aircraft-Based Concept Developments
ANSP	Air Navigation Service Provider
ATC	Air Traffic Control
ATFCM	Air Traffic Flow and Capacity Management
ATFM	Air Traffic Flow Management
ATO	Actual Time Over
ATOT	Actual Take-Off Time
CASA	Computer Assisted Slot Allocation
CDM	Collaborative Decision Making
CFMU	Central Flow Management Unit
CIR	CFMU Interactive Reporting
CTO	Calculated Time Over
CTOT	Calculated Take-Off Time
DLA	Delay Message
ECAC	European Civil Aviation Conference
EOBT	Estimated Off-Block Time
ETO	Estimated Time Over
ETOT	Estimated Take-Off Time
FPL	Flight Plan Message (ICAO format)
IFPS	Integrated Initial Flight Plan Processing System

EUROCONTROL

Dynamic Cost Indexing

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***Abstract*--This paper describes the development of a generic tool for dynamic cost indexing (DCI), which encompasses the ability to manage flight delay costs on a dynamic basis, trading accelerated fuel burn against 'cost of time'. Many airlines have significant barriers to identifying which costs should be included in 'cost of time' calculations and how to quantify them. The need is highlighted to integrate historical passenger delay and policy data with real-time passenger connections data. The absence of industry standards for defining and interfacing necessary tools is recognised. Delay recovery decision windows and ATC cooperation are key constraints. DCI tools could also be used in the pre-departure phase, and may offer environmental decision support functionality: which could be used as a differentiating technology required for access to designated, future 'green' airspace. Short-term opportunities for saving fuel and thus reducing emissions are also identified.**

I. Progress during Year 1

A. Project motivation

1) Overview

DELAYS cause airlines to incur high costs. There are environmental consequences too, particularly those associated with additional fuel burn. Some of the financial costs are reasonably transparent and fairly well understood, others are much less well understood. Airlines try to manage these costs by reducing such delays, and their financial impacts, at all levels of planning: from the strategic phase, through to pre-departure slot management, and on into the airborne phase of the flight.

The Cost Index is a parameter set in the cockpit, which determines how the FMS will fly the aircraft. It quantifies choices concerning flying faster to recover delay, or flying slower to conserve fuel. Boeing (2007) cites that many operators do not take full advantage of this tool, although a recent airline case study suggested annual savings by so doing of US$ 4-5 million, "with a negligible effect on schedule". The research project described in this paper develops the concept we describe as 'dynamic cost indexing', which encompasses the ability to manage delay costs for any given flight on a *dynamic* basis, i.e. in an operational context whereby the cost of a delay varies according to the magnitude of the delay and also strongly as a function of other temporal factors such as passenger connectivities.

The project has two parallel objectives. These are to map the types of data which are required to build a generic, ideal dynamic cost indexing (DCI) tool, including the framework for exchanging such data, and also to start building an operational prototype tool within an advanced, existing flight planning software application. By describing and mapping the general model, the objective is to enable airlines to build their own solutions, or improve existing ones. By building an operational prototype, in parallel, the objective is to establish proof of concept and ensure that a practical focus is maintained. The prototype will be built as a module within Lufthansa Systems Aeronautics "Lido OC" flight planning suite.

The DCI framework developed as part of this research also encompasses environmental costs (such as emissions related charges or permits) and impacts (such as contributions to climate change). This will future-proof the DCI concept by ensuring that evolving charges and/or permit schemes may be integrated seamlessly into the both the general model and the prototype.

2) Introduction to the Cost Index

Cost Index (CI) settings vary from manufacturer to manufacturer. Common ranges are 0 to 99 (e.g. Smiths), or 0 to 999[1] (e.g. Honeywell). The lowest value causes the aircraft to minimise fuel consumption and to maximise range. High values cause the FMS to minimise flight time, regardless of fuel cost. In this sense, a low value assumes the cost of time is low and the cost of fuel is high, and vice versa for a high value. The Cost Index is the cost of time divided by the cost of fuel, multiplied by a scalar:

$$CI = \frac{C_{time}}{C_{fuel}} x\ k \qquad \begin{array}{l} C_{time} << C_{fuel} \Rightarrow CI \approx 0 \\ C_{time} >> C_{fuel} \Rightarrow CI \approx [\max] \end{array}$$

In the context of delay recovery, the 'cost of time' may more usefully be thought of as the 'cost of delay'. CI units are kg/min or 100 lb/h, but are often omitted due to the scalar issue: it is more useful to refer to the generic values CI_0 and CI_{max}, representing maximum fuel conservation and maximum delay recovery (minimum flight time), respectively. The optimal cost solution, taking into account the trade-off between the cost of delay and the cost of fuel, usually lies somewhere between CI_0 and CI_{max}.

A flight is often delayed before push-back. Pre-departure delay recovery is an important tool for airlines, often referred to as slot[2] management. The most common method is by re-routeing on an alternative route, with the advantage of an

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[1] Boeing upper settings also include 200, 500 and 9999
[2] CTOT: calculated take-off time

earlier slot but usually at the cost of incurring greater fuel burn.

A very similar trade-off exists once the aircraft is airborne. To recover delay, increased fuel burn could be used (employing a higher CI setting in the FMS) and/or a change could be requested of ATC for a more direct route. Corresponding measures could be applied to slow down and conserve fuel. More details on this will be given later.

Despite the similarities in these methods of delay recovery, it is important to note three key aspects regarding airborne recovery:

- the fuelling decision has already been taken
- it must start early in the flight to be effective
- it is usually dependent on ATC acceptance (often a limiting constraint)

3) Immediate benefits for airlines

Whilst fuel prices are accurately known by airlines, the other part of the CI ratio, the true cost of delay, very often is not. CI values used by airlines are, in many cases, based on very limited supporting cost of delay data. Many airlines will readily concede that the way in which delay recovery decisions are made can be fairly arbitrary, or based on crude rules of thumb, such as pursuing all slot delays greater than ‘x’ minutes, or using a fixed CI value for all intra-European flights, with only irregular adjustments for changing fuel prices, or even none at all. This is because airlines very often do not have the tools or resources to accurately calculate these costs. Echoed later by Boeing (2007), much of earlier commentary made by Airbus (1998) is still just as true today:

> Much progress could be obtained by having airline accountants look into the other time-related costs also. In practice, however, it has been hard for flight operations departments to persuade their airline financial analysts into assessing marginal operating costs. This is probably because the latter have not yet integrated the importance of the cost index itself, largely an unknown concept to their decision-makers … A large variation exists in how airlines actually use the cost index: some of this variation is related to specific operator requirements, some of it may reflect difficulties with the concept that may lead to inappropriate application.

However, it should be stressed that a range of airline operational practice does exist, with some airlines notably more advanced than others. A few already have tools for dynamic delay cost estimation, but even these would not claim that there is not room for significant advance in this area. Through previous research undertaken by the University of Westminster, and at a dedicated open-invitation CI technical meeting held in Frankfurt in August 2007 as part of this project, the views of a number of airlines have been considered in this context. There was strong support at this meeting, and at a subsequent Lido OC user conference in Berlin, in September 2007, for further development: equally to support airlines just starting to use cost indexing, and for those wishing to strengthen existing tools. Many airlines have a significant barrier to identify which costs should be included in ‘cost of time’ and how to quantify them. In addition, the absence of industry standards for defining and interfacing such tools has been highlighted.

This project is committed to tackling these problems and sharing the results with the airline community, from whom invaluable feedback and support are welcomed and gratefully acknowledged. An overview of two more advanced cases of operational practice is given in section II.A.1.

4) Environmental benefits

As the political position relating to emissions charges remains uncertain, this project aims to deliver a flexible framework in this context, which will serve two main purposes:

- to ensure that both the DCI general model and prototype remain useful and relevant should emissions related charges or permits be introduced
- to allow airlines to consider emissions in their decision-making process in response to delay, allowing them to monitor how this affects such emissions: which may become particularly relevant for airlines wishing to use good environmental practice as a marketable competitive advantage (an aspect of emerging importance to many airlines)

The inclusion of environmental costs has a strong link with the vision for an ultra green air traffic system in 2020, set out by the Advisory Council for Aeronautical Research in Europe (ACARE, 2004). This vision sets out specific targets for improved environmental performance by airports, aircraft, airlines and air traffic management. For ATM, the vision includes the use of ‘green routes or areas’, to provide an incentive for aircraft to be equipped with improved environmental technologies. The vision also includes the specification of an ‘environment signature’ for each aircraft to be included in flight plans and regionally, or centrally, environmental impact assessments to compute optimised 4D trajectories. By including emissions, the framework developed in this project will contribute to the realisation of this vision. It offers an environmental decision support tool for airlines, which could be used as a differentiating technology required for access to designated ‘green’ airspace. The framework combines an ‘environment signature’ with airline costs, providing valuable support for collaborative decision-making between airlines and air traffic management both pre-tactically and during flight, allowing both environmental and economic impacts to be considered.

The development of these types of decision support tools to enable cost-effective optimisation of environmental performance could also contribute significantly to the SESAR objective of reducing the environmental effects of flights by 10%, specifically by addressing excess fuel consumption (SESAR Consortium, 2006). Such considerations relating to fuel burn could, in particular, be related to:

- assessment of route extension fuel penalties to reduce slot delays
- avoidance of unnecessary (and costly) extra fuel burn to recover delays which are not financially worth recovering (e.g. those with few connecting passengers on the delayed

airborne flight and/or where the connecting flights at the destination are already also delayed)
- accelerated fuel burn offsets from the potential for reducing off-stand holding at airports by freeing waiting aircraft from gates, thus improving local air quality

5) Datalink context

This project also assesses how the technology of datalink might be used more in the facilitation of DCI. Datalink is already used by Lido OC to send a variety of messages to the cockpit, including FPLs, NOTAMS, CTOTs and free text. Direct changes cannot be poked to the FMS, i.e. the pilot has to select '[ACCEPT]' to uplinked messages to pass them into the FMS[3]. This would apply to FPLs or proposed CI changes, for example. Due to FMS memory constraints[4] on the number of routes which may be stored, it is often very useful to send a new FPL to the cockpit in this way.

Datalink also plays a central role in Lido OC's flight-watch tool, 'AeroView', for dynamically monitoring the progress of flights. AeroView automatically sends (uplink) messages requesting position, altitude and remaining fuel data which generate automatic (downlink) replies, i.e. without pilot intervention.

Furthermore, datalink is also a key mechanism for airlines to receive information pertaining to aircraft intent, which is an important consideration in the DCI context. If a change to the planned flight profile is instigated by either independent pilot request or by ATC, the airline's operations control will not ordinarily be aware of this (see section I.B.1) unless the pilot informs them, usually by a downlink message.

Whilst ACARS[5] is mostly used off-gate, the at-gate analogue, 'gatelink', is a two-way ground/ground communication link based on standard IEEE[6] protocols, e.g. over a wireless local area network (WLAN). Once connected at the airport (typically within a range of 100 metres of the gate), the cockpit becomes a node on the airline's IP-based network, with a high rate of data transfer (often several hundred times faster than ACARS).

Not all airlines are currently exploiting these technologies. In section II.A.1, where two airline cases are overviewed, the use of datalink will be looked at in the context of operational practice.

B. Methodology

Figure 1 illustrates the relationships, in a simplified way, between the various elements of delay management. Cost to the airline is clearly a key element: the more costly a particular delay, the more effort the airline will be willing to expend to resolve it. The ability of given aircraft to recover from delay is based on both the aircraft's performance characteristics (e.g. how fast in can fly) and the airspace procedures (e.g. what ATC will allow). The darker solid lines represent strong interactions: it is clear, for example, that both aircraft performance characteristics and airspaces procedures affect the environmental impact of the flight.

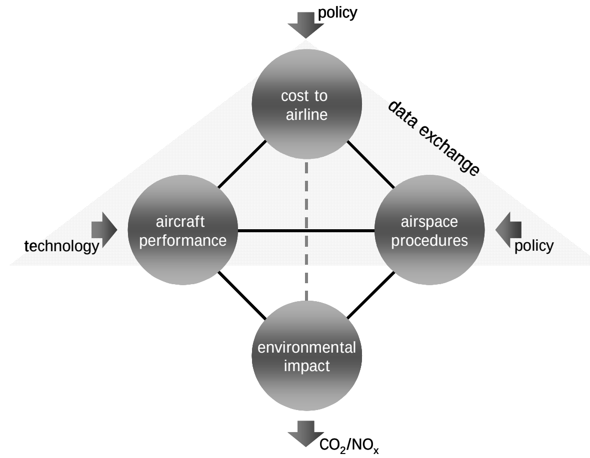

Fig. 1. The wider context of delay management

Currently, the interaction between airline costs and environmental impacts are weak (represented by the lighter, dashed line), but this situation is likely to change. Exogenous factors such as technology and policy affect the upper three elements. Policies such as military access to airspace, and indeed, environmental considerations, determine airspace procedures to a considerable degree. External policies such as EU compensation regulations for delayed passengers, along with internal airline policies on crew remuneration, determine the actual cost of a delay to the airline. Acting as a 'cement' between these elements is data exchange.

In specific terms of DCI, three primary aspects may be considered:

- aircraft performance
  - communications with the aircraft, e.g. ACARS message to speed up / slow down
  - operational capability of the aircraft to adapt speed
- cost to airline
  - internal data management, e.g. on predicted passenger missed connections
- airspace procedures
  - ATC/ATM communication, e.g. to facilitate delay recovery

Whilst Figure 1 is primarily illustrative in nature, in serves to show the important elements of DCI which need to be considered as a whole. The desire to avoid incurring costs is a primary driver of AO behaviour. Actions taken to recover such costs are constrained by both aircraft performance and airspace procedures. Data exchange is a primary enabler of delay recovery, without it, neither the true costs of delay can be computed, nor is there any means to manage the delay. As

[3] Whilst, on the one hand, this represents a constraint on pilot flexibility, on the other hand it is a safety issue, as the FMS has no 'rollback' functionality if a proposed solution is not applicable or acceptable to the pilot. The FMS can't hold more than one route at the same time, such that an update will delete the current information.

[4] Such constraints may currently be overcome by using Electronic Flight Bag applications, some of which may still run on stand-alone devices (such as laptops) in the cockpit.

[5] Aircraft Communications, Addressing and Reporting System

[6] Institute of Electrical and Electronics Engineers

a consequence of the way the delay is managed, different environmental impacts result. The coupling between this impact and the associated cost to the airline is set to become stronger.

A DCI tool which does not fully consider the wider operational constraints, and which is not in an adequately integrated data environment, will not work. These four elements are discussed in turn, in the following sections.

1) Airspace procedures

Dynamic cost indexing relies on being to able to vary aircraft speeds to arrive at the destination at economically optimised times. To understand two constraints on this process, it is necessary to establish the context of both airspace procedures (current practice and restrictions) and aircraft performance (the capability of speeding up or slowing down, for example).

Whilst arrival management in TMAs is frequently achieved through the use of speed control, usually in combination with heading and altitude constraints, en-route separation is normally managed in European airspace through these latter two alone (be that through the airways structure or controller instruction). The focus of attention in the context of delay recovery is on the en-route phase, for two reasons. Firstly, this is the longer phase in the vast majority of cases; it is difficult to achieve large alterations to the arrival time during the more limited time the aircraft is in the TMA. Secondly, other pressures – not least separation and runway management – are more severe in the TMA.

In the en-route phase, speed control is less favoured probably because it requires higher controller monitoring. As EUROCONTROL's Performance Review Unit (2005) point out, whilst en-route sequencing is common practice in the US[7], it is hardly ever used in Europe. Where it does exist, this is on the basis of bilateral agreements between neighbouring ACCs. Ehrmanntraut and Jelinek (2005) report that the effect of speed control to resolve aircraft conflicts has not been well described in the literature, and although speed control may be used in conflict resolution, only *very* rarely do clearances in Europe involve speed in upper en-route sectors. Their paper further states, however, that "speed manoeuvres have a very high potential for [multi-sector planning] … by applying very low speed adjustments". From RAMS (Reorganized ATC Mathematical Simulator) computations, it goes on to conclude: "Best results are achieved when … one [controller] applies speed and the other one a horizontal manoeuvre".

In terms of speeds adopted by aircraft, an analysis by Lenka (2005) shows considerable homogeneity of ranges:

> … 89.8% of the CEATS [Central European Air Traffic Services] traffic prefers 10 different speed ranges out of proposed 36. The most preferred speed range 446-450 NM/h is used by 1500 aircraft representing 29% of the traffic, followed by 857 aircraft (16.5%) with the speed between 456-460 NM/h and 685 aircraft (13.2%) with the speed between 426-430 NM/h. These three speed ranges show high potential to be assigned to the inbound traffic for synchronization purposes.

In terms of operational variances for given aircraft, Averty *et al.* (2007) suggest that controllers are typically exposed to such variances of +3% to –6% (more usually only ±3%, in fact) and that such orders of change impose no significant increase in perceived controller workloads and remain largely unnoticed in normal conditions, citing Ehrmanntraut and Jelinek (2005a), these authors go on to comment that:

> … between FL320 and FL400, speeds are very homogeneous: all aircraft flying within this altitude range have a cruise speed between 430 and 470 kts

Evidence therefore suggests that the typical speed variances to which controllers are exposed are relatively low. Indeed, Averty *et al.* (2007) further comment that:

> … ATCOs are not expected to monitor accurately/specifically speed changes, as these rarely vary as long as aircraft maintain their cruising altitude (en-route airspace). Such changes occur in relation with a few specific events (head or tail winds, turbulence, etc.)

Controllers can call up flight plan data with the planned speeds of aircraft entering their sector and check by RT if the (ground) speed appears to be inappropriate. However, the controller's focus of attention will be on separation, such that whilst this looks secure, speed variations of the order referred to above are unlikely to be noticed. As mentioned, this is made less of a critical issue by the fact that aircraft on the same cruising altitudes tend to be operating at rather similar speeds.

In terms of en-route aircraft actively wishing to change speed, regulations (ICAO, 1990) specify that if the average TAS[8] at cruising level between reporting points varies, or is expected to vary, by ±5% or more of the speed declared in the flight plan, this should be notified to ATC. (Such regulations refer to "inadvertent changes", which has caused some confusion, as discussed in section II.A.2). In such cases either a manual adjustment would then be made by ATC in the Flight Data Processor, or, for more advanced systems[9], this would be automatically detected by the system which would also recalculate the internal flight profile.

For long-haul flights *from* the IFPS Zone, for example to the US[10], FPLs are normally filed well in advance of the Scheduled Time of Departure (STD), to avoid 'late-filer' status, such that by the time the aircraft is airborne, en-route conditions may well suggest a better routeing (in addition to, or instead of, a speed change). In this case, the airline may request ATC to file an air-filed flight plan (AFIL[11]) on their

[7] Known as 'Miles in Trail' – the distance required between consecutive aircraft on a given flow, usually to the same destination.

[8] True Air Speed.

[9] An example is the Swedish case, whereby SAS may request a fuel conserving 'ecocruise' or 'ecodescend'. In this case Luftfartsverket's ATC system ('E2K') automatically computes a new flight profile.

[10] *Eastbound* transatlantic flights are not subject to ATFM regulations, since the departure airports are outside the IFPS Zone, although some flights from outside this Zone may still be subject to ATFM slot allocation.

[11] AFIL: a flight plan submitted to IFPS on behalf of an airborne aircraft by an ATS unit (controlling the aircraft at that time, or into which airspace the aircraft wishes to fly). If instigated by the airline, it first sends this normal-format flight plan message to ATC (e.g. from Lido OC). The departure aerodrome text is replaced by "AFIL".

behalf. Usually, however, the intent to change a flight plan en-route is driven by ATC itself. Instruction is passed by ATC to the aircraft by RT, or, increasingly via ACARS, then it sends an AFIL to IFPS[12].

2) Aircraft performance

As already discussed, the minimum cost solution for a given flight lies somewhere between CI_0 and CI_{max}. The question then arises as to the relationship between CI_0 and CI_{max} and the minimum and maximum speeds of the aircraft. In other words, how tightly does the $CI_0 - CI_{max}$ envelope sit within the performance envelope of the aircraft? This envelope is defined by V_{MU} and V_{MO} which are, respectively, the minimum and maximum operating speeds of the aircraft, signifying limits which should never be disregarded[13].

Furthermore, in order to set DCI into its en-route context, it is necessary to quantify the performance envelope itself in terms of the speed changes available to aircraft at typical cruise levels. Reference to Jenkinson *et al.* (1999) suggests values in the range of 5 - 7%. Based on EUROCONTROL's 'Base of Aircraft Data' ('BADA'), Ehrmanntraut and Jelinek (2005) used speed variances of up ±7.5% in their RAMS simulations. Our calculations, also based on a range of BADA aircraft, gave very similar results at cruise levels, with much higher envelopes at lower altitude, as indeed also shown by Ehrmanntraut (*ibid*.).

In terms of the 'inner' Cost Index envelope, Airbus technical documentation (Airbus, 1998) shows that CI_0 and CI_{max} correspond pretty closely to V_{MU} and V_{MO}, respectively.

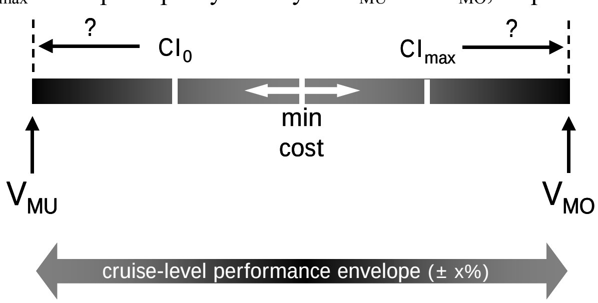

Fig. 2. The wider context of delay management

In practice, the speed used for flight planning with CI_0 is usually a little above V_{MU} (because V_{MU} is too unstable to operate at, e.g. in turbulence) and CI_{max} is a little below V_{MO} (because V_{MO} actually results in a very high rate of fuel burn with approximately no gain in speed, relative to a value just below it). Boeing (2007) uses very similar settings.

CI values not only affect speed, but other performance characteristics, such as turning and climbing. Higher CI values (assuming time is more important than fuel burn) produce higher speeds during climb, with a shallower climb path resulting in Top of Climb being further out, although it is reached slightly sooner. Conversely, Top of Descent occurs later.

It is important to note, however, that airlines do not usually use the full CI envelope, as touched upon above. This is due to a steeply diminishing return on fuel burn with respect to time saved at high CI values, plus the negative effects of increased cockpit and cabin noise at such higher speeds, which reduces both passenger and crew comfort. For these reasons, airlines usually define a limiting CI value for their operations, which will vary by aircraft type. In practice, very low values of CI are also normally avoided, due to negligible differences in fuel consumption for non-negligible flight time reductions. CI_0 is normally only selected if there is an abnormal fuel concern.

At optimum flight levels, Airbus data (*ibid*.) suggest working speed envelopes of 4-6%, making the following useful summary points regarding altitude and weight (author's emphases):

> … ECON speed is very sensitive to the cost index when flying *below* optimum altitude especially for low cost indices, a sensitivity effect which is rather reduced around and above optimum flight level.

> … ECON cruise Mach stays *fairly constant* throughout the flight for representative cost indices … as well as for representative weights and flight levels.

Having established the operational context of the Cost Index within aircraft performance parameters, the main driver of delay costs – delayed passengers – is assessed in the next section. Other airline costs will be addressed within the scope of this project, but passenger costs are the Year 1 focus in this respect.

3) Cost to airline

Passenger costs resulting from air transport delays fall broadly into three categories:

- 'hard' costs borne by the airline (such as rebooking and compensation costs)
- 'soft' costs borne by the airline (such as loss of market share due to passenger dissatisfaction)
- costs borne by the passenger, not passed on to the airline (e.g. potential loss of business due to late arrival at a meeting; partial loss of social activity)

The latter category is not of direct concern to this research, since it is internalised by the passenger. The objectives of this study are only to quantify those passenger costs which directly impact the airline. Indeed, the inclusion of these costs is at best rather arbitrary and can lead to highly inflated generalised cost estimates if not treated with caution.

Of the two categories borne by the airline, both are difficult to assess. The 'hard' costs are difficult to compute due to the problems involved in integrating the necessary data. It is an objective of this research to resolve this as far as possible.

'Soft' costs are problematic to quantify because of the number of complex assumptions which must be made when modelling them, plus their strong dependence on market conditions (such as service availability and price structures). By the end of this study, a crude methodology will be

[12] In fact, *only* to IFPS, such that the airline is often unaware of this, which can be problematic. These changes are often driven by CFMU requests, for ATFM purposes.

[13] All four of these parameters are also a function of weight, altitude, temperature and wind.

suggested to enable airlines to estimate and adjust these costs according to different operational assumptions.

Returning to the 'hard' passenger delay costs, these refer to actual, measurable, bottom-line costs incurred by an airline as a result of delayed passengers, such as those due to: right of care (under Regulation (EC) 261/2004), re-booking / re-routeing costs, and compensation.

LH405	O/D	Timetabled		Act/Estimated		Status		DELAY			Pax cost EST	12077
A343	JFK	2125	01 JAN	2134	01 JAN	IN	OUT	DEP DLY	9	ACT	Pax cost MAX	16162
7h40	FRA	1105	02 JAN	1235	02 JAN	OFF	ON	ARR DLY	90	EST	Pax cost MIN	8002

Seat	Pax	This leg class	This leg fare	Miles & More / FFP	Onward connex	Next leg	Next leg fare	Next leg class	Connex pieces in hold	MCT	Connex flight DLY	Next avail. rebook	Est. DLY at final dest	Cost rebook / re-route	Cost 'care' /compensat'N
1A	1	J	3652,00	MMS	INT	ARN	604,00	C	2	60	20	SK	180	610,00	200,00
1B	1	J	3652,00	MMS	INT	ARN	604,00	C	0	45	20	SK	180	610,00	200,00
1D	1	C	2946,25	MMS	DOM	MUC	415,50	C	1	45	10	LH	120	0	100,00
1E	1	C	2039,55	NO	NO	-	-	-	-	-	-	-	90	-	0
1G	0														
1H	0														
2A	1	C	2946,25	MMFT	NO	-	-	-	-	-	-	-	90	-	50,00
2B	0														
2D	1	C	0,0	MMFT	INT	LON	555,25	C	1	60	0	BA	110	650,90	50,00
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
36A	1	Y	1163,45	NO	NO	-	-	-	-	-	-	-	90	-	0
36B	0														
36C	1	Y	1163,45	NO	NO	-	-	-	-	-	-	-	90	-	0
36D	0														
36E	0														
36F	1	M	266,50	NO	INT	LON	95,30	M	2	60	20	LH	130	0	25,00
36G	1	Y	176,60	NO	INT	OSL	80,60	Y	2	45	60	-	60	-	0
36H	1	Y	176,60	NO	INT	OSL	75,25	Y	1	45	60	-	60	-	0
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
46A	1	Y	266,50	NO	NO	-	-	-	-	-	-	-	90	-	0
46B	1	Y	266,50	MMM	DOM	MUC	80,30	Y	1	45	10	LH	120	0	0
46D	1	Y	176,60	SAS/B	INT	CDG	94,80	Y	1	60	0	AF	145	110,30	0
46E	1	Y	266,50	SAS/B	INT	CDG	94,80	Y	2	60	0	AF	145	110,30	0
46F	1	Y	176,60	NO	DOM	KLN	57,80	Y	1	45	5	LH	120	0	0

Notes

Example data only. All costs in Euros. All times local.

MCT = Minimum Connect Time

FFP =Frequent Flyer Programme (Regulation 261/2004 applies to 'free' tickets issued under such schemes - see Article 3)

Lufthansa Miles & More levels: "Member" (MMM), "Frequent Traveller" (MMFT), "Senator" (MMS), "HON Circle" (MMHC)

Fig. 3. Example of dynamic pax data required by flight

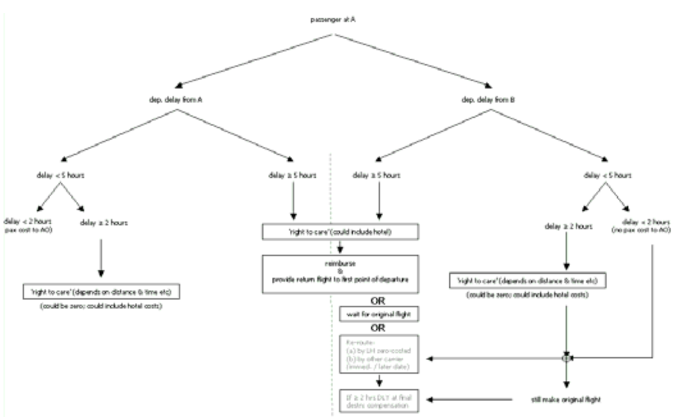

Fig. 4. Delay cost scenario decision tree: example of static pax data required

In order to assess these costs fully it is necessary to have access to both the data in Figure 3 for any given flight, on a *dynamic* basis, and also, for the same passengers, to be able to populate the (mostly) static decision tree in Figure 4, which is both a function of airline policy and EU law (Regulation (EC) 261/2004). Figure 4 is structurally based on the Regulation, which came into force on 17 February 2005: it only relates to departure delay (nothing is legally due to the passenger for any type of arrival delay *per se*), denied boarding, and cancellation. It confers passengers with rights only at the point of departure.

From the perspective of Regulation (EC) 261/2004, nothing is due to a passenger as a result of a missed connection *per se*. Therefore, with a Lufthansa conjunction ticket JFK-FRA-CDG, nothing would be due as the result of a late arrival at FRA, even if the connection is missed, except:

TABLE 1
EXAMPLE OF PASSENGER RIGHTS ACCORDING TO REGULATION (EC) 261/2004

Case 1	If the JFK – FRA flight is delayed by five hours or more <u>and</u> the passenger decided not to fly on it (in which case a reimbursement would be due, and a flight back to the point of origin – if applicable, i.e. the passenger was connecting at JFK)	In which case the passenger would not even be on the JFK-FRA segment
Case 2	'Right of care' (e.g. a meal) at FRA, if the <u>CDG</u> flight itself was delayed by two or more hours (i.e. nothing is due to the passenger specifically on account of <u>arriving</u> late in FRA)	In which case the cost would be attributable to the FRA – CDG segment
Case 3	If the FRA – CDG flight was delayed by five hours or more <u>and</u> the passenger decided not to fly on it (in which case a reimbursement would be due, and a flight back to JFK)	

Figure 4 can also be used to understand departure delay without any connecting flight, by following the left-hand side of the figure. Grey text (centre) means that a right is not afforded by Regulation (EC) 261/2004 as a result of delay. It is to be noted that no additional compensation *per se* (i.e. above reimbursement) or re-routing is required by the Regulation as a result of any amount of delay. This again emphasises the need to integrate 'company' policy into this scheme, in particular:

- compensation policies
- re-booking policies and, taking Lufthansa as an example, how these vary:
  - internally (whether allocated at zero cost for LH – LH re-booking)
  - within STAR alliance (e.g. special arrangements with SAS)
  - with other carriers (typical costs; any special arrangements by route / ticket class)

Such static data could be integrated with the dynamic data of Figure 3 to build a continuously updated estimate of the current cost of the unrecovered delay. Figure 3 shows that with the current arrival delay of 90 minutes, an estimated total of € 12 077 passenger delay costs would be incurred. Data flagged red in the 'MCT' and 'connex flight DLY' columns indicate a missed connection. It is noteworthy that this design allows the airline to set different policies for different passengers, for example by giving special care to the high-yield and/or higher status frequent flyer programme members. This does indeed happen in practice; several airlines have the capacity to differentially and dynamically track a problem with a delayed high-status passenger – some can even determine if the same passenger has recently suffered a delay on one of its services.

Further practicalities of this approach will be explored later in this paper. For now, it is important to identify the importance that: proper consideration is given to the decision windows involved in delay recovery (it is obviously too late to recover a delay in the final stages of a flight); data on connecting flight status may not be available; the database(s) must protect confidential airline data such as fuel prices and special compensation policies. It is also important to note that there will very often be no economic advantage to recover the *entire* delay: allowing say five minutes to persist will often not incur any (significant) airline costs but will save unnecessary fuel burn.

4) Environmental impact

Carbon dioxide

Once emitted, carbon dioxide remains in the atmosphere for hundreds of years and becomes uniformly mixed by atmospheric motion. As a result, the climate impact of 1 kg of emitted CO_2 does not depend on the altitude or location of emission. The amount of carbon dioxide emitted by combustion of fuel depends only on two factors, the carbon content of the fuel, which for kerosene is typically 71 500 kg/TJ (IPCC, 2006), and the amount of fuel burned. This allows fuel consumption to be used as a direct indicator of carbon dioxide emissions. The main institutional mechanisms for regulating carbon dioxide emissions from aviation are the Kyoto Protocol and the proposed extension of the EU Emissions Trading Scheme to include air transport.

The Kyoto Protocol requires that domestic aviation be included in national carbon dioxide emission inventories and in emission reduction targets for Annex 1 signatory countries. Emissions associated with fuel sales for international flights are reported separately. These emissions are excluded from national reduction targets under the terms of the Protocol, which instead called for action to be pursued through the mechanisms of the International Civil Aviation Organization (United Nations, 1998).

In December 2006, the European Commission issued a proposal for legislation to bring aviation into the European Emissions Trading Scheme (European Commission, 2006). The proposed design would impose a cap on maximum CO_2 emissions from aviation, with aircraft operators required to undertake monitoring and reporting, and to surrender permits covering their emissions. The negotiation process is ongoing and the scheme design is not yet finalised. ICAO have produced draft guidelines for the participation of aviation in emissions trading schemes, with a preference for open schemes: allowing aviation to be a net purchaser of emissions permits from other industries (ICAO, 2007).

The Intergovernmental Panel on Climate Change recommends three methods for calculating emissions from aviation for reporting purposes. Tier 1 is based only on fuel sales, while Tier 2 uses fuel sales in conjunction with standard data for Landing-Take Off (LTO) procedures. Tier 3 is the most detailed approach and is based on flight movement data. Tiers 2 and 3 are more accurate at differentiating between international and domestic emissions. Tier 3 offers the best disaggregation of emissions by individual flights (IPCC, 2006).

Nitrogen Oxides

The European Commission has pledged to develop a proposal to address nitrogen oxide emissions from aviation by the end of 2008 (European Commission, 2006). The form this proposal will take is uncertain, but includes a number of options for corresponding measures to operate alongside emissions trading for CO_2 (Wit *et al.*, 2005). There are existing restrictions on NO_x emissions in the LTO cycle administered through ICAO's Committee on Aviation Environmental Protection. The effectiveness of extending these limits to control NO_x emissions at cruise altitudes is not clear. The limits apply to the certification of new aircraft engines, so there would be a significant delay before new emissions restrictions would apply across the full aircraft fleet. Other options include modifying airport landing charges according to certified LTO NO_x emissions. This is in use at some airports as an air quality measure, but again it is uncertain whether providing incentives to reduce low altitude NO_x emissions would be an effective way to reduce emissions at cruise. The option that would most accurately address cruise altitude NO_x emissions would be an en-route charge based on emissions calculated from the fuel flow rate and applying an emission index based on aircraft type and adjusting for temperature and humidity (Wit *et al.*, 2005).

In addition to the uncertainty surrounding proposed legislation, several factors complicate the inclusion of nitrogen oxides (NO_x) in the DCI framework. While carbon dioxide emissions are proportional to fuel burn, NO_x emissions depend on the background atmospheric conditions. The climate impact of such emissions depends on their altitude and location; reducing cruise altitude can increase NO_x emissions but reduce the climate impact. NO_x emissions at typical cruise altitudes have two competing climate effects. Methane concentrations are reduced which has a cooling effect; the ozone concentration increases, contributing to warming. These two effects do not simply offset each other. Methane has a longer lifetime than ozone, and the spatial patterns of the two effects are very different. At cruise altitudes in the stratosphere, NO_x emissions can reduce, rather than increase, ozone. Our approach to NO_x emissions is discussed further in section II.C.

5) Integrating emissions into flight planning

For integrating CO_2 emissions into the DCI framework, Tier 1 and Tier 2 approaches would be too coarse to allow any fine level resolution to be made regarding delay management decision-making. We propose an approach which is consistent with the most detailed option (Tier 3b, in fact) which is based on flight trajectory as well as aircraft and engine data, and by calculating CO_2 emissions on a flight-leg basis. This methodology will integrate with existing functionalities of Lido OC, which is capable of outputting fuel burn at the flight-leg level (although users rarely require such data).

Looking ahead to Year 2, it has been commented above that the option that would most accurately address cruise altitude NO_x emissions would be an en-route charge, based on emissions calculated from the fuel flow rate, applying an emission index based on aircraft type, and adjusting for atmospheric conditions. This would also be highly suited to the flight-leg model, and suggests an additional functionality of identifying emissions within national boundaries, following the way en-route ATC charges are currently calculated in Europe.

By considering potential CO_2 and NO_x calculational requirements together, and taking the common approach of a flight-leg model which is able to respect international boundaries, allows a flexible and future-proofed solution to be constructed. Figure 5 shows an example flight plan with corresponding flight-leg data in Table 2.


```
-B738/M-SDRPWY/S
-EGLL1500
-N0444F330 DVR6J DVR UL9 KONAN UL607 SPI UT180 DITEL T180
 POBIX/N0414F230 T180 OSMAX OSMAX3E
-EDDF0057 EDFH
-EET/EGTT0008 EBUR0017 EDVV0041 EDUU0041 EDGG0047
```

Fig. 5. Extract of LHR - FRA flight plan, with map

By using a real flight plan as a test case, i.e. planning with permitted routeings and altitude restrictions, with knowledge of national boundaries, it will be possible to populate each flight leg with planned fuel burns based on historical data for a given aircraft (i.e. with actual knowledge by tail-number) for typical meteorological conditions and ATC practice. These results will be presented in the next section.

TABLE 2
LHR – FRA FLIGHT PLAN: PLANNED ROUTE AND TIMING, WITH RESTRICTIONS

Phase	State	From	To	Elapsed time (@ 'To')	On		Permitted planning
Climb	EG-EG	EGLL/09R	DET	0009	DVR6J	SID	(see text)
	EG-EG	DET	DVR	0012	DVR6J	SID	(see text)
	EG-EB	DVR	KONAN	0015	UL9	airway	>FL 250 – FL 660
	EB-EB	KONAN	KOK	0018	UL607	airway	FL 195 – FL 660*
	EB-EB	KOK	FERDI	0023	UL607	airway	FL 195 – FL 660
	EB-EB	FERDI	BUPAL	0028	UL607	airway	FL 195 – FL 660
Cruise	EB-EB	BUPAL	REMBA	0029	UL607	airway	FL 195 – FL 660
	EB-EB	REMBA	SPI	0033	UL607	airway	FL 195 – FL 660
	EB-ED	SPI	DITEL	0037	UT180	airway	FL 195 – FL 660
	ED-ED	DITEL	BENAK	0037	T180	airway	6000 – FL 660
	ED-ED	BENAK	POBIX	0039	T180	airway	6000 – FL 660
	ED-ED	POBIX	AKIGO	0040	T180	airway	6000 – FL 240
Descent	ED-ED	AKIGO	OSMAX	0041	T180	airway	6000 – FL 240
	ED-ED	OSMAX	EDDF/07L	0103	OSMAX3E	STAR	(see text)

Notes
* KONAN-MATUG not FL270
Navaids at: DETLING (DET), DOVER (DVR), KOKSY (KOK) & SPRIMONT (SPI) (other points are waypoints only)

C. *Key results for Year 1*

Whilst much of the work undertaken in Year 1 has been invested in developing the methodology, this section presents key quantitative outputs based on our initial calculations. Table 3 completes the calculations defined by Table 2.

TABLE 3
LHR – FRA FLIGHT PLAN: PLANNED SPEED AND ALTITUDES, WITH OUTPUTS

Phase	State	From	To	On	True Air Speed (knots)	Flight Level	ATC (€)	Leg fuel (kg)	LegCO2 (kg)
Climb	EG-EG	EGLL/09R	DET	SID	(VAR)	*≤ FL 250*	156	1005	3206
	EG-EG	DET	DVR	SID	≤ 444	*FL 250 – FL 330*		203	648
	EG-EB	DVR	KONAN	airway	444	FL 330		184	587
	EB-EB	KONAN	KOK	airway	444	FL 330	288	124	396
	EB-EB	KOK	FERDI	airway	444	FL 330		192	612
	EB-EB	FERDI	BUPAL	airway	444	FL 330		188	600
Cruise	EB-EB	BUPAL	REMBA	airway	444	FL 330		61	195
	EB-EB	REMBA	SPI	airway	444	FL 330		139	443
	EB-ED	SPI	DITEL	airway	444	FL 330		153	488
	ED-ED	DITEL	BENAK	airway	444	FL 330	117	15	48
	ED-ED	BENAK	POBIX	airway	444	FL 330		68	217
	ED-ED	POBIX	AKIGO	airway	444 - 414	FL 330- FL 230		6	19
Descent	ED-ED	AKIGO	OSMAX	airway				13	41
	ED-ED	OSMAX	EDDF/07L	STAR	(VAR)	(VAR)		357	1139

After take-off, the aircraft is subject to a series of AIP-published instructions for the DVR6J SID, notably not to exceed 250 knots below FL 100 (unless instructed otherwise), not to climb above 6000 feet (until instructed), that the en-route cruising level will be issued by ATC after take-off, and that the aircraft should be levelled off at 6000 feet as it approaches DET. In practice, the aircraft is normally at FL 250 by DET (which is 50NM from EGLL/09R: ATC usually takes the aircraft off the SID as soon as possible) and the fuel calculation in Table 3 reflects this practice (with the aircraft actually at or below 6000 ft for 8NM from EGLL/09R to an intermediate waypoint). As shown in the flight plan, it is desired that the aircraft be established on FL 330 at 444 knots from top of climb.

Similarly, the AIP arrival instructions for the OSMAX3E STAR detail that once cleared from the OSMAX holding pattern, the aircraft follows a series of waypoints, not descending below 5000 feet. Once the REDLI waypoint has been reached, the aircraft is not to exceed 250 knots; beyond REDLI, the aircraft is not to descend below 4000 feet until instructed by ATC.

The calculation of CO_2 emitted, in the last column of Table 3, utilises an energy content of aviation kerosene of 44.59 $TJ/10^3$ tonnes, established by the IPCC (1996), and a CO_2 emission factor of 71 500 kg/TJ (as cited in section I.B.4). This gives the result that 3.19 kg of CO_2 is emitted per kg of kerosene consumed.

In Year 2, this framework will be extended to allow emissions *cost* data to be computed, using a common flight-leg approach for both CO_2 and NO_x. Whilst this framework will exceed likely operational requirements as far as permits and charges are concerned, the user will be able to relax the settings to produce simpler values. Towards next incorporating time saving functionalities into the framework, typical CI values used by airlines were used to produce Figure 6, based on a LIS – HEL (longer range) flight.

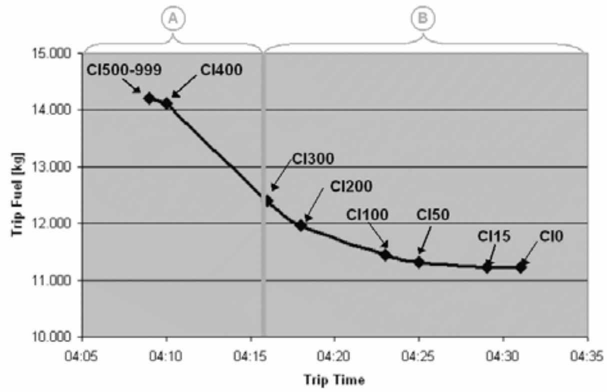

Fig. 6. LIS - HEL trip time v. trip fuel, by various CI values (B737-800)

As introduced in section I.B.2, airlines do not usually use the full CI envelope. Zone A in Figure 6 represents an area of technically possible operations which an airline would not ordinarily choose to use. Ignoring the non-linearity issue, Figure 6 can be mapped back onto Figure 2 to give an illustrative, updated version of the latter, as shown in Figure 7.

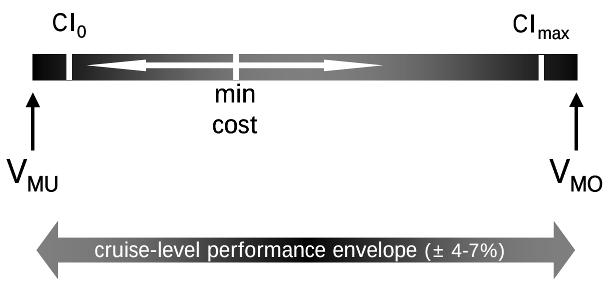

Fig. 7. The wider context of delay management (refined)

This information can now be used to explore a series of realistic time savings, across 23 simulated flights[14], as given in Table 4[15]. The values in this table, showing time and fuel differences, thus relate to the corresponding differences exemplified by zone B in Figure 6, for each of the airport-pair flights considered, from CI_0 to $CI_{max(B)}$. Values also depend on payloads, engine types, known tail-specific fuel consumption correction factors, and different lateral routes and vertical profiles. Typical settings have been used in the table, the only difference between the fuel and time values being the different CI applied. These results will be discussed in section II.A.2.

TABLE 4
TIME SAVINGS ACHIEVABLE ON 23 SELECTED ROUTES

Route & aircraft				$CI_{max(B)}$ values		Differences: $CI_{max(B)}$ c.f. CI_0			
						Extra fuel burn (kg)		Time saving (min)	
Ref. code	Route	GCD (NM)	ACFT	CI	Flight time	Total	Per min time saved	Per hour flight time	Total
01\07	CDG-LHR	188	A320-200	200	00:39	120	60	3.1	2
02\08	AMS-LHR	200	B737-500	200	00:41	70	35	2.9	2
03\05	TLX-FRA	233	A300-600R	400	00:54	120	30	4.4	4
04\06	DUB-LHR	243	A321-200	500	00:47	140	47	3.8	3
05\02	FCO-LIN	254	ERJ 175LR	100	00:47	50	17	3.8	3
06\01	MAD-BCN	261	ERJ 190AR	500	00:51	180	90	2.4	2
07\14	CPH-OSL	280	A319-100	200	00:48	70	35	2.5	2
08\04	EDI-LHR	288	B757-200	500	00:49	60	30	2.4	2
09\17	MAD-PMI	295	ERJ 175LR	100	00:58	20	10	2.1	2
10\10	ARN-CPH	296	B737-800	300	00:51	120	60	2.4	2
11\03	ORY-TLS	309	A318-100	90	00:48	130	65	2.5	2
12\16	ORY-NCE	364	F100	100	01:02	110	22	4.8	5
13\09	FCO-CDG	595	A310-300	500	01:30	930	155	4.0	6
14\18	FRA-MAD	769	A321-200	500	02:01	1110	123	4.5	9
15\20	IST-DUB	1594	A319-100	200	03:54	950	73	3.3	13
16\19	LIS-HEL	1819	B737-800	300	04:16	1180	79	3.5	15
17\13	LHR-DXB	2972	A340-600	500	06:17	5600	350	2.5	16
18\11	LHR-JFK	2993	B767-300	300	07:01	3000	94	4.6	32
19\15	LHR-YYZ	3083	A330-200	400	06:45	3770	209	2.7	18
20\12	CDG-JFK	3152	B747-400	500	07:23	4000	154	3.5	26
21\23	BKK-FRA	4865	A340-500	500	10:51	14120	300	4.3	47
22\22	HKG-LHR	5204	B777-300ER	500	11:49	7010	152	3.9	46
23\21	SIN-FRA	5558	A380-800	500	11:57	12070	302	3.3	40

Notes
Load assumptions available on request
Manufacturers: A = Airbus, B = Boeing, E = Embraer, F = Fokker

II. DISCUSSION, PROGRESS IN YEAR 1, PLANS FOR YEAR 2

A. *Discussion*

Having discussed the key challenges which AOs face in the context of effectively implementing DCI solutions, it is instructive to briefly overview, as illustrative examples, the cases of two airlines which are particularly advanced in their use of this method: SAS and Air Canada. We will then discuss the broader context of our results.

1) *Summary of two airline case studies*

SAS have two basic approaches to time-managed arrivals. For long-haul, although repeated position update reports are made through ACARS, the flight crew will inform operations control if they judge that the Cost Index needs to be adjusted to recover anticipated arrival delay, awaiting a response on whether to do this or not. This dialogue also occurs through ACARS.

SAS wishes to move more towards firmer rules for decision-making, for example deciding when there is no net financial benefit of recovering a specific aircraft's delay, or of holding a connecting flight. The carrier plans to incorporate

[14] The detailed selection rationale for these 23 routes was given in Technical Discussion Document 3.0. See section III.

[15] Despite the typical settings used, it should be noted that the timings and fuel burn figures in Table 4 should not be taken as absolute values, as clearly they will vary according to upper air temperatures and winds, which are constantly changing. These flight data were based on flight plans calculated 17-22 OCT 07. Taking the LIS-HEL flight as an example, under the same input assumptions, this was calculated as taking 29 minutes longer, when computed a few days later.

the full use of the DCI concept by 2009, thus moving away from the current practice of recovering all delays on short-haul.

Short-haul experience has shown that when two ETAs are produced, one based on the wheels-off time (ETA_1) and a subsequent estimate based on a position report some 10 or 15 minutes later (ETA_2), then by integrating these with the flight plan and meteorological data, both ETA_1 and ETA_2 produce close, and robust, estimates of the actual arrival time (i.e. continuous position reporting is not usually required on short-haul). Furthermore, for these flights, SAS is able to integrate these data in real-time with connecting aircraft and crew rotation data, although currently (only) to define, as a first step towards full DCI, the latest arrival time that has zero delay cost. Approximately 10 minutes after the wheels-off message is processed by operations control, an ACARS message is sent to the aircraft with this latest, zero delay cost arrival time. As a second step towards soon realising its DCI concept, incremental fuel burn will be balanced with costs per minute of arrival delay.

Air Canada used to carry additional fuel on those flights where the potential missed connection cost was above a common, fixed-dollar threshold, but recently decided not to uplift extra fuel solely for the eventuality that a delay might arise en route, due to sharp increases in fuel prices. Attempts are still made to recover time solely using the fuel on board whenever it is practical (i.e. using additional fuel which was planned for other reasons, such as potential airborne holding or weather), although sophisticated decision-making is still undertaken prior to push-back.

Flights are operated using city-pair defined Cost Index values and utilize the VSOPS[16] feature within Lido OC to determine when a flight may be planned at this (lower) Cost Index value, or the default (higher) value at which the flight was originally planned. This method sometimes allows operations at lower speeds, thus conserving fuel, but operating at higher Cost Index values when required, i.e. in order to maintain schedule.

Other manipulations of Cost Index values are based on whether the dispatcher proposes specific settings when the airline's custom-built software tool computes this to be cost beneficial. This tool computes the costs of delays of predetermined values (e.g. STA[17] + 10 mins, STA + 20 mins) which are then traded-off against increased fuel burn. These costs include passenger and crew costs; both of these are based on historical data. The passenger costs notably not only include hard costs (such as hotel accommodation) but also estimates of passenger loss of future value ('goodwill'). Marginal maintenance costs, based on the powerplant element of 'A' Checks (which are determined by flight hours) are also factored in. Air Canada wishes to devolve more decision-making to the pilot (c.f. the SAS long-haul model), but currently faces the task both of integrating their in-house system with Lido OC, of sharing this information with the cockpit (especially with respect to dynamically computing the implications of using various Cost Index values), and obtaining reliable data on in-bound delays to build a better network picture. The latter may be realised through Lido's flight-watch tool, 'AeroView'.

[16] Variable Speed Operations
[17] Scheduled Time of Arrival

2) Discussion of way forward – plans and challenges

The foregoing discussion can now be synthesised into a detailed data architecture for DCI, describing which tasks are to performed where, as shown in Figure 8. Notable in the cockpit context is the role the pilot may play in future decision-making, enabled by improved CI and (dynamic) ACARS data, as also suggested by the SAS and Air Canada case studies.

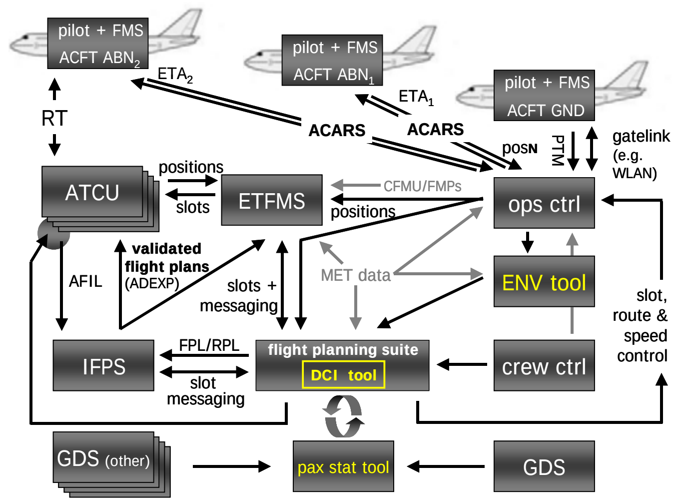

Fig. 8. Detailed data architecture for DCI

Although Passenger Transfer Messages (PTMs; see top-right of figure) were investigated as an earlier part of our methodological investigations, it seems that these standard-format, passenger-connectivity messages are usually sent too late for the purposes of DCI. In Year 2, therefore, a high priority will be set for further exploring better dynamic passenger data in the Lufthansa case study context, despite the discontinuation of Lufthansa Systems' FACE (Future Airline Core Environment) passenger management platform (see section II.B).

The benefit of drawing on historical passenger data has been clearly highlighted during our discussions with airlines, as a necessary and invaluable complement to the dynamic data. This is an important finding. In essence, historical data can play an important role in helping to estimate dynamic delay costs due to passenger missed connections. This is partly due to the fact that repeated evolutions of delay situations in the past can often be a better cost predictor than partial dynamic data: the true connectivity picture is rarely complete in the complex tactical context of an airline network. Furthermore, static data are also required for estimation of compensation costs, for example, as discussed in section I.B.3, which must be based on AO-specific rule bases. Thus, reflecting the practice of several airlines, it is envisaged that our passenger statistical ('pax stat') tool will incorporate static data as well as interfacing with dynamic (GDS) data.

As represented by the revolving-arrow motif above the 'pax stat' box, this tool would use data such as that held in the database of Figure 3, to iterate the best DCI solution for a given flight. As mentioned earlier, this often would not be expected to resolve an optimised solution at zero delay, thus possibly saving unnecessary fuel burn in many cases. Pre-departure fuel uplift and other decision windows must clearly be respected. As with the passenger statistical ('pax stat') tool, whilst our emissions ('ENV') tool would actually be part of the DCI module within the flight planning suite, it is elaborated in Figure 8 outside of this box to show its particular additional data connectivities, in this case with meteorological and operational (e.g. aircraft specification) data.

Table 4 has shown that the scope for delay recovery on short-haul routes is quite limited. Indeed, SAS expects that flights of under 60 minutes should usually be flown with a low CI. Recognising such limitations may save other carriers significant fuel burn and emissions consequences. Nevertheless, several airlines have identified that even smaller delay recoveries can be worth the fuel penalty in terms of increasing arrival predictability and the minimisation of tactical disruption at the airport. It is clear, nonetheless, that the greatest delay recovery opportunities lie with longer-hauls, in addition to the ATM predictability benefits identified by EUROCONROL (2005): "En-route speed control with required time of arrival (RTA) could … reduce variations in arrival times on transatlantic flights, provided RTA is applied well in advance".

Closing on a practical ATC point, scope also remains for clarifying the operational constraints of applying speed adjustments, as touched upon in section I.B.1. Of particular note here is the recent conclusion of an ICAO Sub-Group meeting (ICAO, 2007a) regarding regulations pertaining to allowed variations in TAS, saying it is:

> … evident that there is a general lack of a common understanding as to what the phrase, "Inadvertent Changes" means … Both groups agreed that a common understanding is critical in today's operating environment where reduced separation standards are being implemented and that clarification is needed as to the true intent of this section. […] Many of the modern day aircraft are flying Fuel Cost Indexes, where the Flight Management System automatically makes variations in speed throughout the course of a flight.

B. *Progress in Year 1*

Whilst we have been able to make good progress defining our methodology and system architecture, in addition to significant development of the passenger database requirements, maturing the passenger interface has been slow due to the unforeseen discontinuation of Lufthansa Systems' FACE (Future Airline Core Environment) passenger management platform, on which we had planned to develop our functionality. The extension of the project at this early stage to include a number of other airlines has been seen as a particularly progressive step (see also section III). Work on the NO_x framework, scheduled for Year 2, has been more advanced than anticipated.

C. *Plans for Year 2*

The full design of the incorporation of NO_x emissions into the DCI framework is a task to be undertaken in Year 2 of the project. Characterisation of NO_x emissions will be consistent with the en-route NO_x charging model described. It will maintain the flight-leg approach used for CO_2 and will take into account the IPCC reporting methods for NO_x. These use a standard LTO cycle, then an aircraft-specific emission index based on fuel consumption for cruise emissions (IPCC, 2006). The framework will include the option for a weighting function to reflect the dependence of impacts on the altitude of emission, which will include lower altitude fuel burn estimates. We may extend the functionality to incorporate CO_2 uplift factors. APU emissions will not be modelled. Modelling crew costs will proceed as planned, hopefully drawing on practice from airlines invited to contribute to this component.

We currently estimate that Year 2 actions and deliverables will be one month later than planned in our proposal, with the exception of the end-of-year deliverable.

In terms of changes to our original proposal for Year 2, we propose to replace the inclusion of airport charges in the framework with the significant additional maintenance costs incurred, e.g. due to increased engine wear as a result of delays and/or higher CI settings during delay recovery. This has partly been prompted by AO request at the August 2007 DCI workshop, and partly due to new approaches to this challenging computation which might now be more tractable.

Looking further ahead, to the possibility of Year 3 work, potential exists for adding noise signatures into the framework (e.g. with time of arrival and departure weightings) and other air quality emissions (beyond NO_x), again drawing on lower altitude fuel burn models. Other options include modifying airport landing charges according to certified LTO NO_x emissions. This is in use at some airports as an air quality measure, but again it is uncertain whether providing incentives to reduce low altitude NO_x emissions would be an effective way to reduce emissions at cruise. This could be closely linked to re-including the airport charges in Year 3, currently proposed to be dropped from Year 2.

III. Key Publications, Outputs and Milestones

Technical Discussion Document 1.0, *Scoping 'hard' passenger delay costs to the AO*	12 February 2007
Technical Meeting 1, Lufthansa Systems Aeronautics, Frankfurt	12-13 March 2007
Technical Meeting 2, University of Westminster, London	30 April 2007
Presentation of DCI concept at UK ATM Knowledge Network Meeting, London	04 June 2007
Technical Discussion Document 2.0, *Summary of emissions schemes*	15 June 2007
Technical Discussion Document 3.0, *CI scenario route*	23 August 2007

proposals	
Airline Dynamic Cost Indexing Workshop, Hotel NH Frankfurt Rhein–Main, Frankfurt (Attended by: EUROCONTROL; Air Canada, CSA, Emirates, Finnair, Lufthansa, Qantas, Qatar and SAS)	28 August 2007
Dynamic Cost Indexing: paper in preparation for peer-reviewed journal	November - December 2007

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MAMMI Phase2 – Design and Evaluation Test Bed for Collaborative Practices on En-Route Control Positions

Stéphane Vales, Stéphane Conversy, Jérome Lard, Claire Ollagnon

Abstract—**The MAMMI project studies ways to improve the collaboration between ATCOs on the same position, using modern ATC concepts and tools, and explores new opportunities for dynamic organizations and workload management. This paper presents the problems considered by MAMMI and the design and evaluation test-bed that will help progressively introducing and evaluating new solutions, with the overall objective to get relevant operational feedback.**

Index Terms—**multi-touch and multi-user interaction, mutual activity awareness, tasks and workload sharing, tactic planner dynamic organization, collaboration models for Air Traffic Controllers**

I. Introduction

THE MAMMI project started in June 2006 with the objective of exploring how modern control positions could benefit of:

- Improvements of the collaboration between En Route Air Traffic Controllers working as team-mates, which has not progressed, and sometimes has even decreased, on modern digital systems with consequences on situation awareness and efficiency in high workload situations,
- New organization patterns and roles for the ATCOs, providing solutions to the limits reached by the complexity management techniques consisting in reducing the size of the sectors.

These objectives are motivated by several problems detailed in this document, and they rely on the concept of Multi Actors Man Machine Interfaces (MAMMI), proposed by EUROCONTROL Experimental Centre. The MAMMI concept is composed of three principles:

1. Several ATCOs to interact collaboratively on a single en route position.
2. Real time tasks sharing and workload repartition.
3. Lesser specialization for the ATCOs.

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To explore the MAMMI principles, the consortium of the project has set up several research directions, feeding a participatory and iterative process. This process involves ATCOs and ATC experts from several European countries and aims at providing semi-realistic prototypes suitable to get a relevant feedback from operational users. The prototypes are gathered in the MAMMI test-bed composed of two facets dedicated to the design and to the evaluation of solutions. The definition and the early implementation of this test-bed are presented in this paper.

II. Importance and Nature of the Collaboration between Air Traffic Controllers on Modern Operational Systems

The non-verbal communication has been shown to represent up to 50% of the whole communication acts in a highly cooperative activity such as En Route ATC [1]. Usually, non-verbal communication is done while seeing the co-worker and/or the shared environment. For example, physical co-presence enables co-workers to use multiple sorts of gestures (deictic, passing, utterance-like) that improve common understanding of the situation. Physical distance between co-workers may not weaken performances in a collaborative activity, but it leads them to engage in more demanding communication acts [3], thus requiring additional efforts in their activity. The supplemental work is done at the expense of the main activity, which may be problematic in a situation where work is complex and cognitive load is high. Furthermore, knowing that the other knows as much as oneself makes the interpretation of the other's intentions easier, which in turns makes collaboration better [5], [2]. Multimodal communication involving speech and co-located gestures is better at building mutual knowledge of sharing than speech alone [6].

As teamwork was considered a major asset of previous systems for both safety and efficiency, several questions are raised about newer systems, which rely mainly on digitalized and individualized tools. This section provides additional elements to understand the stakes and issues around teamwork and collaboration between ATCOs, toward safety and efficiency.

A. *Evolution of the airspace*

According to the on-going traffic, sectors composing the En Route airspace can be grouped or split so that the controllers

A. *Evolution of the airspace*

According to the on-going traffic, sectors composing the En Route airspace can be grouped or split so that the controllers always have to manage a reasonable number of aircrafts. This way to manage the complexity of the traffic is the most commonly practiced at the moment. However, it is reaching a limit in a sense where sectors become so small that aircrafts cross new sectors every few minutes, implying an important communication activity both between controllers and pilots for frequency change, hello/goodbye messages, etc., and between controllers from different sectors for more and more coordination purposes.

If this direction is confirmed, the current model of always smaller sectors controlled by a tactic and a planner controller might reach its limits, even with efficient sector grouping/splitting procedures. This shows the interest of studying other organisations, especially regarding the roles of tactic and planner ATCOs, and the way they collaborate.

B. *Evolution of the control positions*

On modern control positions, each controller is using his/her own interaction means, consisting in a keyboard and a mouse. The progressive disappearance of the paper strips leads to a sort of "glass cockpit" effect imposing several potential disadvantages to the ATCOs.

First, the control positions are designed for two separated users, without any direct possibility to exchange information or actively discuss on a shared support. This forces the ATCOs either to work more independently, or to make efforts to create a common context, most of the time only by voice, to exchange analysis with their team-mate. The key concept of mutual situation awareness is, by the way, only poorly supported by the modern systems, either explicitly with dedicated functions, or implicitly by natural usages that the ATCOs might have built upon the basic functionalities.

Then, as each ATCO has his/her own tools (tactic and planner have different configurations), the organisation is rigidified by the system itself. The opportunities to delegate tasks between tactic and planner are strongly conditioned by the way the system has been designed. And as the systems have not been designed with strong considerations about collaboration, ATCOs have to cope with this rigidity in their every day activity.

This provides elements indicating that adding new functionalities dedicated to collaboration might not be sufficient or relevant to provide a good collaboration. On the one hand the number of functionalities on current systems is already very high: the constraints on the training, the efficiency and the saturation of the HMIs become a real stake in this context. On the other hand, a proper introduction of this kind of functionalities requires the evaluation of the impact on the global design of the control tools offered by the control position, and maybe also on the interaction means mandatory to support the collaboration, in a way, for instance, a paper strip board used to support it. This is linked to the frequently observed situations where ATCOs under heavy workload, massively change their use of the modern digital tools and abandon most of them to rely mainly on their short term memory and cognitive resources. This presents the requirements on the tools of the control position to provide an extended flexibility for these situations and to integrate seamlessly into the ATCOs' cognitive processes.

C. *More than two controllers on the same position?*

The control positions are designed for two separated controllers. However, interviews that have been conducted since the beginning of the project on French ATCOs show that during more than 50% of the time, more than two controllers (generally three) are working on the same control position at the same moment. The third controller can be there either for training or to help managing the on-going traffic. This simple fact reveals that thinking a control position for two users only is limiting and does not really help the efficiency or the collaboration, especially when the controllers really need it, during (not so) unusual situations.

In the same way, having a third controller on a given control position implies a new repartition of the roles compared to the one foreseen for tactic and planner team-mates. This suggests first a need for the control tools and devices to support this new and dynamic organisation. Then, even when only two ATCOs are on the position, it might be possible to provide them with an additional flexibility they could take advantage of.

D. *Nature of the collaboration*

Several studies [7], [8] have extensively explored the cognitive mechanisms used by the ATCOs. They describe how the ATCOs manage information, use their memory, and how their cognitive workload evolves. In parallel, the training received by the ATCOs includes rules and principles for the collaboration between tactic and planner, and with other sectors, based on the tools available on a control position.

However, only few studies focus on the real-time collaboration between En Route ATCOs. And when they do, the associated recommendations are based either on the modification of the practices or on the evaluation of specific functionalities (new or not) without an objective of designing a homogenous set of tools that would really be collaboration-oriented.

The first consequence is that, based on these studies, it is particularly difficult to get a global vision of the collaboration between En Route controllers. The actual practices of the controllers and the way they use their system to collaborate has been barely described, because they are hard to capture, especially when they have not been foreseen by the system designers initially. Output from a recently launched study of EUROCONTROL could provide interesting information on this topic (TRS T07/11041SA "Team Coordination study" to be started on 7/1/7).

The second consequence is that on a system that is neither collaboration-centred, nor designed to enable some flexibility, the ATCOs have to circumvent the limits of the system, by imagining solutions on their own. This phenomenon is not the sign of a non-adapted system but it authorises to think that a collaboration-friendly system, imagined from the beginning to facilitate collaboration, could enable to take advantage of both modern (with real added value) and old (with flexibility and good situation awareness) systems.

These considerations raise the need to explore the collaboration between ATCOs on the same position under a new scope, oriented on real-time operations and with a more global approach including all facets of the control activity, in order to provide first a relevant analysis and then adapted design solutions. This challenge requires an adapted strategy, inline with the resources of the MAMMI project and the current state of the art for the collaborative practices. This strategy is presented in the next part.

III. A TEST-BED FOR THE DESIGN AND THE EVALUATION

The MAMMI test-bed is the global result of the first year of the project. It puts together the technological, software and HMI resources to create a couple of frameworks suitable to experiment and evaluate the MAMMI principles and solutions. This chapter presents the first version of the test-bed composed of:

- The design framework which enables to produce and expose design solutions to the ATCOs and ATC experts. It provides the necessary components to iteratively compose an innovative control position oriented toward the collaboration between ATCOs around the MAMMI principles.
- The evaluation framework which enables to run the design solutions in a semi-realistic context, based on recorded traffic to put the ATCOs in almost operational conditions so that they can provide an accurate feedback.

A. Why a test-bed approach?

The previous chapter shows the difficulty to find recent exploitation data for the collaborative practices between ATCOs in the different European control centres. The MAMMI project might not have sufficient resources to generate these data. To cope with this constraint while producing relevant solutions, the MAMMI partners have chosen a participative and iterative methodology, supported by rapid prototyping techniques. This means that the design process is animated by a continuous involvement of the end-users, i.e. the ATCOs. They are involved in the production of solutions and in their almost immediate evaluation. This requires an environment that is modular and reactive enough to support this flexibility.

The MAMMI test-bed enables to introduce and evaluate progressively the different facets of the foreseen collaborative control position, without waiting for a complete set to be available and avoiding any long break in the participation of the ATCOs.

All the efforts engaged in this first half of the project were to design this test-bed which is meant to become the major asset for the final success of the project and the evaluation phases.

B. The design framework

At this stage of the project, the design framework serves as a proof of concept providing a first set of components paving the way to a more complete control position. These first components have been imagined based upon interviews and design sessions with the ATCOs and ATC experts. They provide basic concepts for the collaboration and raise questions to be answered later on in the project with experimentations where they will be used by ATCOs facing recorded Air Traffic, as explained in 0.

1) High level organization of the position

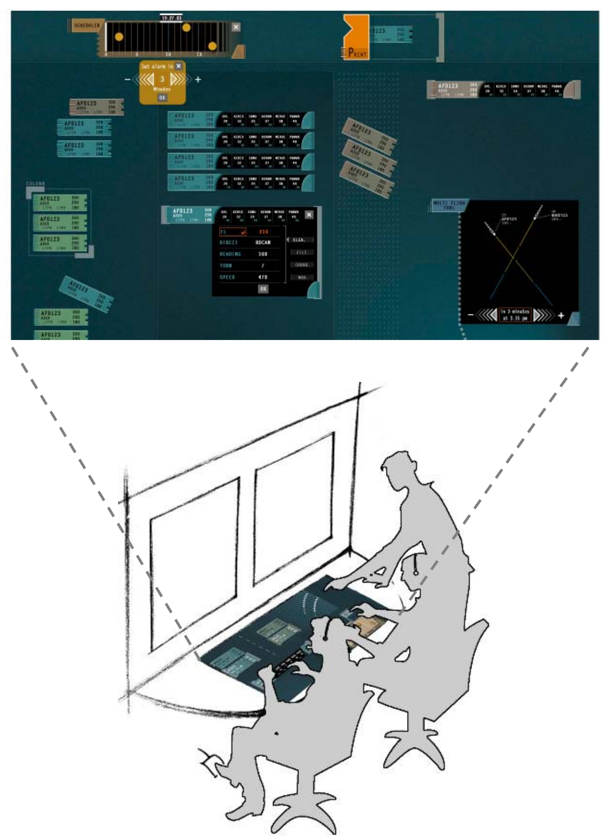

Fig. 1. A potential MAMMI position

The hardware arrangement foreseen for a MAMMI control position is the following:

- Two radar displays are presented vertically on the position. They serve as a reference view of the traffic situation and are dedicated to information visualisation rather than data input. Each display can be configured separately to fit the needs of the ATCO using it.
- A horizontal shared surface is placed below the radar displays. It centralises the input means on the control position, provides all the control tools and enables to setup the radar displays. This shared surface can be used by more than two ATCOs if needed.

This hardware configuration is taken as a base for our design solutions. It will evolve in the next years according to the needs and functionalities that will be considered.

2) *Flights representation and life cycle*

The first concept to define on a control position is the way the flight data are represented and managed. We propose here that each flight is represented by a label, which serves as an entry point for the access to information and some functionality. The labels appear in a printer and are destroyed when dropped onto a shoot box. This set of interactions based on direct manipulation and supported by an advanced graphic design, has been proved [9], [10] to be specifically adapted to the collaboration between ATCOs.

Fig. 2. A label

Fig. 3. The printer

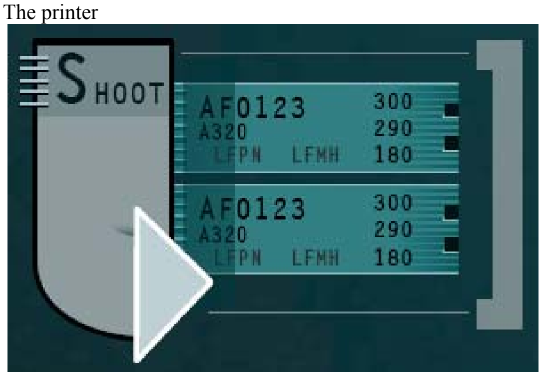

Fig. 4. The shoot box

The labels are moved when a user presses their left part with his/her finger and moves it.

The labels offer an extended view, which could be qualified as a ‘strip view’, enabling to show the route of the represented flight. The switch between the standard view and the strip view is achieved with a two fingers interaction or by placing the label on specific areas as explained here below.

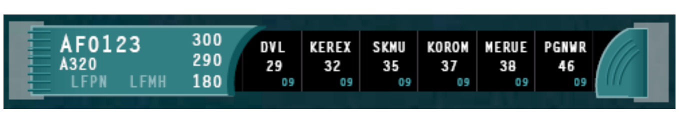

Fig. 5. The strip view for a label

The labels can also be rotated with a two fingers interaction. This enables an ATCO to catch the attention of his/her team-mate on specific flights with minimum effort.

Fig. 6. A rotated label

ATCOs can also take into account a flight explicitly. This is a reproduction of a classical and fundamental action used on paper strips to indicate to the team-mate that the flight is acknowledged and that the context it brings with it is correctly understood.

Finally, we propose to select the labels with the effect of giving feedback of this selection on the radar display, by highlighting the flight and display its route. A selection by a given user will be displayed on his/her display. If a user selects several flights at the same time (through multi-fingers interaction), these flights are all highlighted on the radar display.

QuickTime™ et un
décompresseur TIFF (non compressé)
sont requis pour visionner cette image.

Fig. 7. Labels with different feedbacks

The representation of the flights and the way they can be manipulated and highlighted are key factors for the construction of mutual situation awareness on the control position. The direct manipulation with fingers is much more easily perceived by team-mates than manipulations with a keyboard and a mouse.

The natural capability to organize the labels on the horizontal surface enables a natural share of the surface between private spaces for each controller and common spaces used for exchanges. The usual life cycle of the labels can thus be easily reproduced and even extended.

The way the ATCO will be able to use all the possibilities of the manipulation, of the orientation and the different highlighters to create their own language and communicate one with the others will be a major part of the MAMMI results.

3) *Writing pad and columns for the underlying organisation*

The organisation of the labels over the shared surface can be supported in different manners. The first one we propose here is a writing pad filling the background of the surface. This writing pad provides static information and is not meant to be interactive, just like a physical writing pad, laying on a desktop, can be. Several writing pads have already been considered:

- Geographical, representing a sector, its boundaries and its beacons. It enables to organise the labels with a geographical approach, easily indicating for instance conflicts areas and entry points for the flights.

- Workflow, representing different areas associated to a state of the flight. It is close to the use of existing paper strip boards with richer possibilities like an adaptation of the visualisation (standard vs. 'strip view') according to the position of the labels.
- Terminal sectors, to organise the flight according to their Flight Level, as shown, for instance, in the ASTER prototype from DSNA/DTI/R&D.

The second element for the organisation is the mobile column. This can be seen as a mobile container suitable to move or manage several labels at the same time. Depending on the writing pad, it could be used for instance to create stacks or to sort the flights by routes, flows, etc.

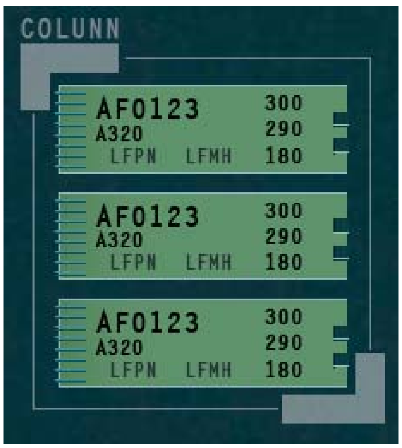

Fig. 8. A column with three labels

In this approach for the organization, we provide the ATCOs with an important flexibility, sustained by a given writing pad giving the global framework. The test-bed will enable the following observations:

- Evaluation and creation of new writing pads which will also provide interesting information on how the ATCOs organise their workspace when they are free to do so, even dynamically.
- Use of columns for a more personalised, individual and quick organisation. The meanings associated to the columns will also enable to express and experiment the classification techniques used by the ATCOs, especially in a collaborative context.

4) Clearances, modifications, tools and concept of association

Beyond the organisation of the flights, ATCOs also need to input data or use advanced tools to improve their perception and their analysis of the on-going traffic. Our initial proposition consists in two components:

- The input tool, enabling to operate clearances, modifications, coordinations, etc. to a specific (set of) flight(s). This tool is available within each label and independently (see below).
- The multi-flight tool, enabling to access advanced functionalities related to several flights. At the moment and as a proof of concept, we propose only a separation tool, which provides a representation to detect if several flights are conflicting and when.

The proposed way to summon these tools is explained here below.

To trigger the functions brought by the input tool and the multiflight tool on specific flights, we introduced the interaction of association: the left part of each label and the writing pad enable to draw curves when a user moves his/her finger on the interactive surface. This enables to create visual links between the different objects like labels and tools. A link between several labels and a tool will be interpreted as a call of the functionality provided by the tool on the concerned labels. This will initialise the tool with the appropriate parameters to be executed.

Fig. 9. The input tool integrated with a label

The interaction of association has already been refined to be robust to the crossing of unwanted objects (through a "short break" algorithm) and to be efficient in a multi-user context with each user having his/her own space.

The main objective of the interaction of association is to give a quick and flexible way to associate objects without needing to move them, knowing that the place of each object is already conditioned by other aspects (classifications, workflows, etc.).

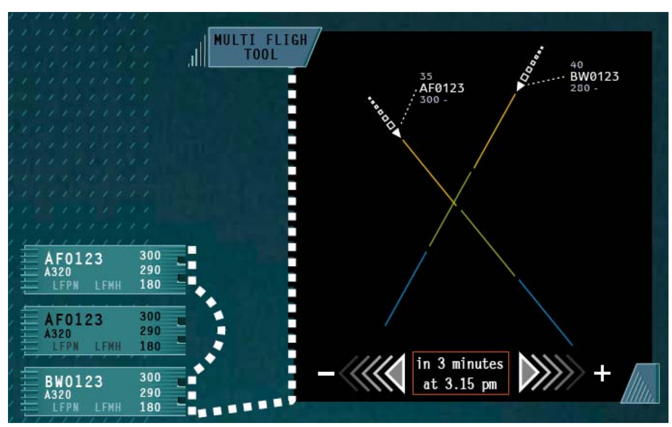

Fig. 10. The multi-flight tool associated with two labels

The global frame defined for the tools gives a large set of opportunities to integrate functionalities proposed by existing systems. Coupled to the capacity to summon and hide tools easily so that the ATCOs always have the right set of tools, this will enable:

- to establish what these set of tools are in the different situations
- to extend the set of tools with potentially missing functionalities
- to minimise the redundancy of information and functionalities on the control position

The interaction of association will also serve as a base for a graphical language whose first extensions are presented later in this paper. The objective upon this idea is to enable the construction of a real language to be used by the ATCOs to compose kinds of sentences corresponding to the tasks they have to achieve. In this perspective, we will try to add a new dimension to the use of ATC tools that is completely missing in existing systems and we would stay compatible with our collaborative context (composition of sentences between several ATCOs).

5) Dynamic invocation pattern

In addition to representations of flights and the tools, ATCOs need to memorise specific information, create notifications (warnings, etc.), apply functions and specific clearances (shoot, direct, change frequency, etc.), all this for a certain number of flights. To study these possibilities, we propose to add a new type of objects called invokers. The invokers are created by gesture recognition on the writing pad. According to the recognized gesture the proper invoker is created.

Then, the invoker can be moved on the interactive surface like any other object. Placed in proximity of other objects and the interpretation by the ATCOs, it can modify its meaning. For instance, a warning invoker placed nearby two flights can indicate a conflict between these two flights, whereas placed over a precise area on the geographical writing pad, it can indicate a thunderstorm.

Fig. 11. The three states of the warning invoker

The invokers are compatible with the interaction of association. According to the type of invoker, an association can mean an actual association or can be interpreted by the system to trigger functions. For instance, a warning invoker associated with two labels will indicate that the warning concerns the two flights represented by the labels. A shoot invoker associated with two labels will send the two labels automatically in the shoot box.

Specific gestures over the writing pad are also used to summon the tools. An interesting point is that the size of the gesture enables to determine the desired size for the tool and the origin of the gesture indicates the position of the tool.

The concept of invoker is the less mature at the moment. This is mainly due to the complexity in the definition and the consistent integration of the different types of invokers, balanced with the definition of tools to avoid any overlap. However, the example of the warning invoker has caught the interest of the ATCOs with a set of actions they achieve frequently on the flights (e.g. force the heading of a flight, set a direct route, change the frequency, etc.). Representing these actions by invokers could significantly lighten some of their most frequent tasks.

6) Time management and notifications

Helping the controllers to anticipate and organise their activity is one of the major stakes of every control position. In our design, we had also to consider all the collaborative aspects and the already introduced concepts. This led us to the concept of scheduler. It is based on a horizontal timeline showing from 0 (now) to several minutes in the future. The length of the timeline can be adjusted.

The scheduler is designed to manage entries that are placed with a chosen duration in the future. The entries then move automatically to the present time. The insertion of a new entry in the scheduler is achieved with the interaction of association. The ATCOs can create an association of several objects and include the scheduler in this association. When the association is completed, a popup is displayed below the scheduler to select duration. When the duration is chosen, the entry is placed accordingly in the timeline. When the time is up for a given entry, a popup is displayed, remembering the list of objects (names or callsigns depending on their type) initially associated to the entry. The ATCOs have the possibility to highlight these objects for a quicker perception.

The associations between the scheduler and other tools may also have a signification. For instance, an association between our multi-flight tool and the scheduler will pre-configure automatically the duration for the entry with the extrapolation time used on the multi-flight tool and the labels used in the tool will be recalled when the entry runs out of time. An entry can be moved or removed by direct manipulation on the timeline even after its creation.

The scheduler has been designed to be extremely flexible both toward its integration with the other concepts and its use by several ATCOs at the same time. With this flexibility, it should enable to observe and provide solutions for the time management on a control position.

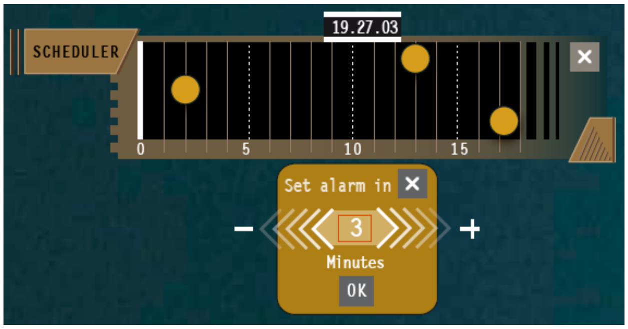

Fig. 12. The scheduler with several entries and a popup

The consistency between the scheduler and the other objects will also enable to position the time management in the panorama of the different concepts and to show the interactions between the time and these concepts to get an accurate design.

7) Perspectives for the ATC usages and the design

On the ATC side, the design framework aims at providing all the mandatory elements to explore the three MAMMI principles presented here above:

- More than 2 ATCOs - the tools and interaction concepts as they have been designed are usable by several users at the same time without any consideration on the number of users. All the objects are all movable to configure the shared workspace easily, even with the possibility to distinguish different areas.
- Dynamic workload repartition - upon the natural flexibility of the tools, which is a mandatory feature providing real opportunities for a dynamic distribution of the activity, the introduction of a shared scheduler will enable, to evaluate more explicitly the anticipation and the delegation of the different tasks completed by the ATCOs.
- Lesser specialisation - the list of provided tools comes from an analysis of the current activity with a tactic and a planner controller. However, the proposed tools and solutions do not make a difference between these roles. This will enable any ATCO to potentially use any tool at any time, providing a flexible framework to explore a lesser specialization of the roles.

On the HMI side, in addition to the design perspectives mentioned above, the project will need to focus on the following directions:

- The organisation of the labels on the workspace will certainly need to be assisted to improve the comfort of the ATCOs. This issue will be explored by the introduction of new objects like magnetic lines or auto-arrangement invokers applicable to selections of labels. These objects will be prototyped in the next six months.
- The feedback and the progression of actions, defined as a requirement, need also to be included carefully, once the concepts for the inputs are well defined. Especially, it will consist in an enrichment of the input tool.
- The preparation of actions (particularly clearances) will also be introduced to explore the possibilities of delegations and anticipations. These concepts will be linked with the use of the scheduler.

C. The evaluation framework

The evaluation framework aims at enabling an efficient and relevant feedback from the ATCOs regarding the proposed design solutions, progressively forming a collaborative control position. To get this feedback, the evaluation framework relies on two main achievements:

- The simulation requires setting up semi-realistic traffic scenarios, so that the ATCOs can be put in a situation where the solutions can actually be tested. And these scenarios have to be supported by instrumented replay tools that support dynamic changes.
- The experimentation of the design solutions is also considered. This experimentation will be based on the traffic scenarios but will also include the collaboration models. As stated previously, these models aim at providing tracks for the design but also at assessing the benefits of our solutions regarding the way the workforce is spent and the opportunities to parallelize the tasks.

1) Simulated control environment

The MAMMI test-bed includes a reference radar display. This radar display application is adapted from previous achievements at DSNA/DTI/R&D (former Centre d'Etudes de la Navigation Aérienne) dedicated to the experimentations with ATCOs. It is also used in the on-going ERASMUS project led by Eurocontrol.

The radar display and the MAMMI software are powered by an application, also provided by DSNA/DTI/R&D and supporting the ASTERIX format to replay real recorded traffic, in accordance with the sectors to be managed by ATCOs in the chosen scenarios and showed on the radar display.

The gathering of two radar displays, the MAMMI software prototypes and the replay application forms an experimental control position that is suitable for our evaluation and experimentation sessions with operational ATCOs, based on semi-realistic traffic situations.

2) Instrumentation of the simulated environment

All the technical aspects of the evaluation framework are already working. The second step is to set up the theoretical and experimental background for the observations themselves. This will be achieved by the end of 2007, in parallel of the completion of the design.

3) Definition of the traffic scenarios

The MAMMI objectives include the assessment of the MAMMI benefits compared to existing solutions. They include also the evaluation of different principles and configurations (roles, number of ATCOs, etc.). This variability requires the definition of traffic scenarios that are large and complete enough to enable comparisons between the different configurations.

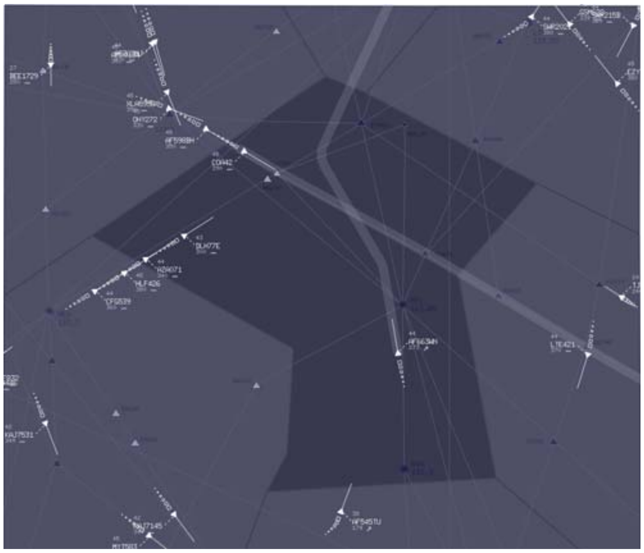

Fig. 13. The radar display

We might for example consider scenarios involving three sectors that could be grouped or even merged. The scenarios will also have to provide a sufficient and representative number of situations including conflicts, inter-sector coordinations, etc. Operational ATCOs and ATC experts already participating to the project are involved in the definition of the scenarios and the selection of the traffic to be replayed.

4) Evolution of the collaboration models

The evaluation framework will first contribute to extend and finalize the collaboration models –that are not presented in this paper as they are not fundamental to expose our current work-, following the evolutions of the design and the adaptations to the different traffic scenarios. Once they are ready, they will be integrated in an experimentation protocol for a more complete assessment, addressing some quantitative aspects. The collaboration models will be the key elements to be used for the analysis different tested solutions.

5) Emergence of solutions and formal validation

The evaluation framework is used as a hybrid. It first informs the designers on the usages of the ATCOs facing the traffic scenarios. The designers include the results of these (basic) experimentations to improve the design from an HMI point of view (quality of the interaction, of the presented information, etc.) and to refine the MAMMI concepts by a cross analysis of the different configurations.

Then, in the last phases of the project, the Human Factors specialists will define a test protocol. This protocol will rely on the collaboration models and will define objective and (some) quantitative variables to conclude, as much as possible according to the resources of the project, on the benefits brought by the MAMMI principles.

IV. Conclusion

Previous studies on collaborative practices between ATCOs on paper-based or older environments show the importance and the interest to understand the collaborative behaviours on current operational positions. In parallel, the natural evolution of the air traffic system shows an arising need to imagine new organisations for the ATCOs to provide alternatives to the reduction of the sectors sizes.

The MAMMI principles proposed by the EUROCONTROL Experimental Centre aim at leading the study in these directions through the use of multi-user and multi-touch surfaces that are relevant, although still experimental, technologies. The novelty of the technologies and the solutions they enable, combined with a relative lack of studies on current collaborative practices used on operational control positions justify an adapted strategy around a test-bed providing means for the implementation and the evaluation of features that enable to reintroduce collaboration-oriented solutions on fully digital air traffic control environments.

The MAMMI project is currently focused on the production and refinement of innovative solutions. The design presented in this paper is the result of 14 months of work, started from scratch in June 2006, knowing that MAMMI is the very first project exploring global collaborative solutions for the air traffic control positions on such hardware as shared surfaces. A new version of the MAMMI test-bed will be achieved until December 2007 and demonstrated at the 6th EUROCONTROL INO Workshop. This version will include the first feedback and comments from the operational ATCOs involved in the project, based on simple traffic scenarios. And this version will also be tested by these ATCOs to engage the next design iteration.

The evaluation side of the test bed is necessarily less advanced as it relies on the design framework to make progress. Moreover, it requires a functional enough position to enable relevant tests with ATCOs. The evaluation framework will be operational for the first time in the December version of the test-bed. After that, the iterations and exchanges between design and evaluation will become quicker and will thus enable a faster convergence to the objectives of the project.

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3D-in-2D Displays for ATC

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***Abstract*—This paper reports on the efforts and accomplishments of the 3D-in-2D Displays for ATC project at the end of Year 1. We describe the invention of 10 novel 3D/2D visualisations that were mostly implemented in the Augmented Reality ARToolkit. These prototype implementations of visualisation and interaction elements can be viewed on the accompanying video. We have identified six candidate design concepts which we will further research and develop. These designs correspond with the early feasibility studies stage of maturity as defined by the NASA Technology Readiness Level framework. We developed the Combination Display Framework from a review of the literature, and used it for analysing display designs in terms of display technique used and how they are combined. The insights we gained from this framework then guided our inventions and the human-centered innovation process we use to iteratively invent. Our designs are based on an understanding of user work practices. We also developed a simple ATC simulator that we used for rapid experimentation and evaluation of design ideas. We expect that if this project continues, the effort in Year 2 and 3 will be focus on maturing the concepts and employment in a operational laboratory settings .**

***Index Terms*—3D-in-2D displays, human-centered innovation, ARToolkit, innovation in visualisation.**

I. Introduction

THIS document reports on our achievements in Year 1 of the 3D-in-2D Display project, funded by EUROCONTROL under the INO CARE III Innovation Research programme. The key outcome of the project this year was the invention of 10 3D/2D display concepts, which for expediency reasons, were mostly implemented in the Augmented Reality ARToolkit. This AR technology allowed us to quickly explore the design space and modify the designs in a rapid and iterative creative cycle, where ideas often spurred the generation of other ideas. These design concepts should be considered as elements that will be combined into a more comprehensive solution when the concepts become more mature. Some of these 10 concepts have been distilled into six candidate concepts for further development and evaluation in Year 2. These six concepts are reported here and may also be viewed in the video clips on accompanying CD and DVD.

In addition, we also developed a Combination Display Framework that allowed us to consider the different designs in terms of the display technique used, and the manner in which they are combined. This proved to be a very useful initial outcome that enabled us to understand the capabilities of a design that arose from the interactions between the way information is rendered and the mechanisms used to manipulate and control what is viewed. Another enabling technology developed this year is the Simple ATC Simulator, which we developed for use as a air traffic control test bed for experimentation and design evaluation. For the needs of creative invention, speed and quick turn-around from a static paper design to a rudimentary animation of the design, was essential to the maturing of the design concepts. Finally, we devised an iterative and creative invention process needed to support the rapid yet systematic generation of novel display concepts. We called this the Human-Centred Innovation Process. It is based on the principle that technological innovation need to be informed by an understanding of human work practices in a way that allows us to design technologies for the future that will not only work, but more importantly, works well for the user.

One key factor that arose in all our discussions was about the maturity of the concepts. We are of the view that our display concepts are at the very early stages of development that correspond with Level 1 and 2 of the NASA 9-point Technology Readiness Level framework. TRL 1 and 2 refer to blue-skies ideas and feasibility studies level of readiness. The technology is many years away from market, while a readiness level of TRL 8 and 9 indicates that the technology is deployable, i.e. "mission qualified" and "mission proven". We expect that the innovations we have researched will have a 15-20 year deployment timeframe, as some of the 2D-based operational concepts can take that time to change.

A. *Background to the project*

The 3D-in-2D Display ideas developed out innovations we developed during an earlier FP6 project, "AD4 Virtual Airspace Management". At the end of the project, in 2007,

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further funding was obtain from EUROCONTROL's Innovation Research Area to devise effective ways of combining 3D and 2D views of air traffic (i) allowing the controller to benefit from the mutual capabilities of the two displays; and (ii) minimizing the effort when moving from one view to the other.

B. *Motivation: Rationale for Combining 3D with 2D*

Various projects have been initiated to develop 3D visualization systems for ATC: stereoscopic visualization systems using device such as goggles and head mounted displays [1], perspective based visualization systems such as the AD4 Virtual Air Traffic Management project [2], where one looks in the scene, rather than being immersed into it. These systems are complete 3D virtual reality representations of entire airspaces under control. If there is a need to see a plan view, the controller has to either (i) switch viewing to another 2D planar display, or (ii) re-configure the 3D display by moving the camera position, to access a top down plan view of traffic.

The motivation for such projects has been to create 3D depictions to minimize the interpretative efforts needed to create a mental model of the situation. Standard 2D radar does not show the third dimensions thus controllers have interpret from alphanumerical digits and to hold in their mind information on the vertical plane. This result in a very demanding cognitive tasks since controllers have continuously construct and update a 3D mental picture made of 3D traffic locations and 3D restricted volumes, such as terrain, weather, wake vortices, positions and geometry. An extensive review of the advantages and disadvantages between 3D and 2D has been reported elsewhere [3] and are summarised in Table 1.

Through our review of the literature, we have found that 3D displays are better for supporting integrated attention tasks. These are tasks requiring the integration of information across three dimensions, such as understanding the volumetric shape of a complex weather front, and instructing an aircraft to descend and turn to intercept the localizer. This cannot be done easily or well in 2D. However, 2D is better for focused attention tasks, such as estimating expected horizontal separation for two converging aircraft.

This situation lead some authors [4-6] to propose to use 3D in combination with the more traditional 2D display since "…the complex demand of many realistic tasks might requires both types of views at different point in time" [5]. However, based on our previous cognitive task analysis and field studies of air traffic controllers work, we wish to do better than to make minor advances that would sill require the display of different 3D and 2D views in a side-by-side configuration. We hope to invent novel visualisations that combine 3D and 2D in a way that compensates the shortcomings of the two display techniques, while collectively exploiting their complementary potential.

TABLE 1
RELATIVE ADVANTAGES AND DRAWBACKS OF 2D AND 3D DISPLAY (ROZZI ET AL., 2007)

Display type	Advantages (+)	Drawbacks (-)
2D Display	Global traffic picture always available Supports correct distance estimation, focused attention tasks [7-9]; Supports improved performances for visual search tasks [10] Easy to orient. User maintain easily orientation awareness (Rozzi 2006) Navigation and Selection are easy to achieve	Do not represent spatially altitude information, and requires the controller to read and interpret alphanumerical altitude data to produce and maintain 3D picture Suffers from cluttering. Overlapping labels and blips difficult to read
3D Display	Supports Superior performance for integrated - shape understanding – tasks [7-9]; Supports development of accurate mental model of traffic and terrain, effective training tool [11]; Supports effective decision making for a/c maneuvering on the vertical plane [12]; Supports at glace assessment of consistency of implemented maneuver with the original one as intended by controller [13]	Hampered distance estimation performances due to perspective distortion effects [11]; Not possible to oversee global traffic/global sector out of camera view [14]; Traffics at the far end of the scene difficult to locate, due to decrease in resolution [15]; Navigation and selection difficult, user can get lost when moving the camera

I. THE COMBINATION DISPLAY FRAMEWORK

The Combination Display is a two-way classification scheme for helping us understand the differences between different yet similar combinations 3D and 2D representations, and the basis for their combinations. It is an early outcome from the research, and is based on a review of about 100 papers describing innovative visualizations in ATC, Command and Control, Medical, Geographic, Engineering and Flow imaging.

This two-way Framework enables us to correlate a display technique such as zooming and distorting how the information is rendered; to a display format such as placing the rendered information side-by-side with a 2D representation of the same information, in ways that might make sense to an ATC controller.

Besides enabling enables us to identify gaps in the literature, the Combination Framework helped us understand the different classes of display that arise from the many possible combinations of display techniques and formats. It also enabled us to identify potential opportunities for further combinations. The Combination Display Framework is presented in Table 2. In relevant cells, we have included some examples of visualisations found in the literature. The Framework as shown in Table 2 also suggests that there are many other possible combinations where designs have yet to be or can be invented. We will next briefly describe the two dimensions of the Framework. For a more detailed discussion, readers are referred to our earlier report D1.1 Innovation and Consolidation Report.

DISPLAY TECHNIQUE	DISPLAY FORMAT				
	Strict 3D	2D/3D Combination Displays			
		Side By side	Multiview 2D/3D	Exo-Vis	In Place
Uncorrelated view (no technique)		St. John ('01)			
3D in 2D symbols					Smallman ('01)
Focus + Context Techniques					
Multiwindows	EC-Lin AR ('06)				PiP Display, AD4 ('06)
Rapid Zooming	Ellis ('87) Azuma ('96) Brown ('94) Eddy et. Al ('99)				
Distortion					Distortion Display, AD4 ('06)
Overview Plus detail			Alexander & Wickens ('03)		
Filtering	EC-Lin VR ('05)	Azuma ('00)	Ilog Display		Lens Display, AD4 ('06)
Multiple Coordinated Views	EC-Lin VR ('05)	Azuma ('00) Furtsenau ('06) D3, AD4 ('06)	Ilog Display		

TABLE 2
COMBINATION DISPLAY FRAMEWORK [ROZZI ET AL.3]

A. *Display Format*

Across the table, the Display Format dimension classifies how 3D and 2D visualisations have or have not been combined. In our reviews, we observe a category of displays that represent the ATC situation is rendered only in 3D, although some offered in combination with different display techniques such as zooming or filtering. The next broad cateogy represents different variations of combining 3D and 2D views. These combined views are the Side-by-side, the Multiview, the Exo-Vis and the In Place views.

The Side by side combination places a 3D view in a different display or monitor beside the screen with the 2D view. In such a combination the controller has to shift his attention significantly across to the other display and to then correlate the identities of the aircraft in the two screens. In a Multiview display, 3D and 2D appear on different views such as within an overlapping window, but on the same monitor. The user does not have to move his sight across different displays and it is possible to link an object of interest in one view, to the same object in other view (ILOG). The Exo-Vis is a class of displays where 3D appears at the centre of the display and from it detailed views are extracted in the form of subvolumes, where 3D or 2D slices are extracted and translated with respect to the original position. In the In-Place view, the 3D visualisation appears in the same frame of reference as 2D, and also replaces the 2D view with the 3D representation. It therefore does not require the user to move from one view to the other. For example the in the AD4 project, we developed a Distortion display. The software developed can be used to turn any selected area of the 2D radar into a 3D space by rotating such area towards the observer, and distorting at the same time the space between the 3D and the surrounding 2D in order to ensure visual continuity.

B. Display Technique

Down the side of the Combination Framework is the Display Techniques dimension which classifies how the 3D and 2D information are rendered. The display techniques include the straightforward rendering of the air traffic situation in 3D. A second approach is to encapsulate 3D information into 2D symbols. In this way 3D information is available at glance and within in the same frame of reference of the 2D information. Such approach has been developed by Smallman and colleagues [10, 16] who found that in visual search tasks for aircraft altitude, heading, and attitude, the use of symbolic 3D information in a 2D display supported faster identification than 3D iconic information in 3D display. The next category of display techniques is referred to as Focus+Context, or F+C techniques. Developed in the field of information visualization to enable a viewer to view in detail information of interest while maintaining the context of that information in sight.

Such a situation exists also in ATC where controllers often need to examine in detail a local tactical problem, reasoning about it in 3D, while needing to know at a glance, what has changed in the global traffic situation which is often presented in 2D. Having the ability to focus on details of interest while also having the context of the situation in sight is vital in maintaining an overall situation awareness that is essential to safety and traffic efficiency.

Simplest among the F+C display techniques is what we call the multi windows technique**.** Contextual or overview information appears in one large window and expanded details are available in related smaller windows [17, 18]. Unfortunately, in this technique the smaller detailed information window often obscures the information underneath it. The rapid zooming technique enables a user to rapidly zoom in and out between a detailed view and a global view of the traffic situation [17, 18]. Distortion techniques have been used in 2D information visualisations to magnify relevant data and suppress details in order to see context. This is demonstrated by the Fish Eye lens technique [19]. The overall-plus-detail technique provides a magnified detail view close to the global view. A marker signals which part is magnified in the separate detail view, so that the user can correlate between the two views. The filtering technique allows us to show additional information in the focus view by filtering or modifying the way that the focus data is presented [20-22]. Modification can be achieve, for instance, by enlarging data of interest, by adding additional information , such as by showing hidden details, or distinguishing them, and by suppressing distracting information. A typical example of this technique is the London Underground map proposed by Leung & Apperley [23]. The F+C techniques reported earlier exploit the spatial properties the display design in order to enable the user to achieve insight with large volumes of data. An alternative is to link and coordinate interaction and information across Multiple Coordinated Views. This approach couples actions carried out in one view with actions in another. These actions include selection and navigation [24] [25], enabling

Selection ↔ Selection;
Navigation ↔ Navigation; and
Selection ↔ Navigation.

C. Using the Combination Display Framework to identify Opportunities for Innovation

We used the Combination Display Framework to: (i) identify gaps and opportunities for innovation in the spectrum of possible combinations. For example no ATC work has been found in the Exo-Vis stream of visualization; (ii) understand the differences between displays and how we can exploit them, (iii) choose among the array of techniques that could be implemented individually or combined with others to create new representation formats; (iv) Understand how our designs compare and therefore avoid replicating the work of others.

II. The Innovative Concepts

We used the Combination Display Framework together with our human-centred innovation approach (to be described in detail later) to create new ideas. 10 readily identifiable novel concepts were developed during Year 1, and have since been distilled to the six key candidate concepts reported here. It should be noted again that these candidate concepts are features and elements, intended to be used in further combination to form a solution. They should not be seen as stand-alone controller's tools or systems. Due to space constraints, readers are referred to report D1.2 Innovative Concepts and their Design Rationale for a complete description of each of the concepts and their design rationale. Note that a video recording of the 6 concepts has been produced on CD or DVD to accompany this report. These videos demonstrate the interactivity and the dynamic visualisation that are essential for appreciating the capability of these designs. These concepts are: (i) AR in your hand, (ii) AR magnifying glass, (iii) AR 3D Wall View for Stack Management, (iv) AR 3D Wall View of Approach Control, (v) Skyscraper and Symbicons, and the (vi) Table Top Display. For reasons of expediency, the concepts were mostly implemented with the Augmented Reality AR Toolkit. Figure 1 maps the development of the different concepts.

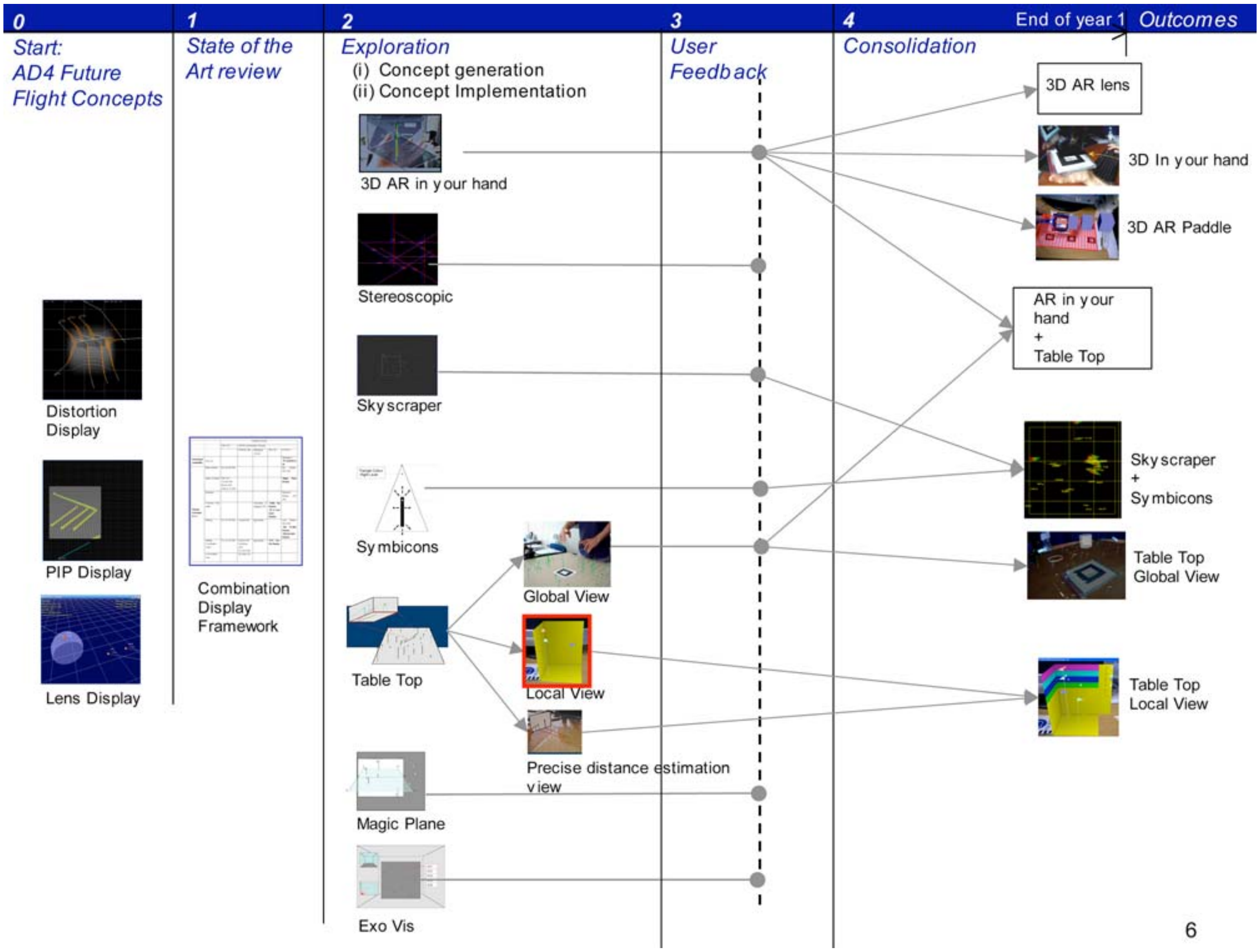

Figure 1. Year 1 development path of the 3D-in-2D concepts

A. AR in Your Hand

The AR ((Augmented Reality) in your hand concept allows a controller to use his or her hand to select a portion of the 2D radar screen, and then have the 3D (or other view) appear in the palm of his or her hand.

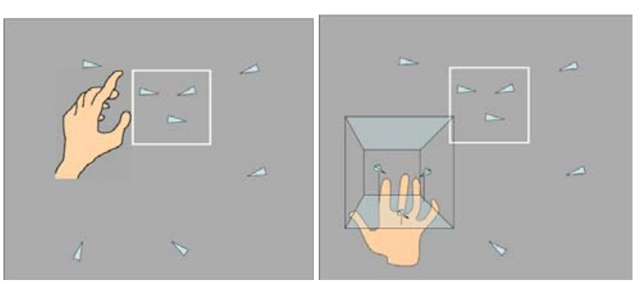

Figure 2. Early sketches shows selecting AR in your hand

In this prototype we use markers to facilitate the process, but in the final implementation, we envisage it would work using just your hand. This process is illustrated in Figure 2. Figure 3 shows the implemented prototype AR in your hand using the AR Toolkit.

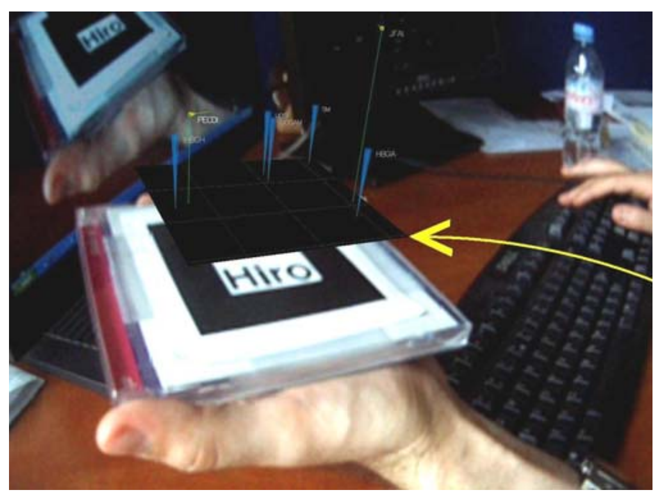

Figure 3. Prototype implementation of AR in your hand.

The AR in your hand display allows a controller to intuitively examine the airspace of interest by rotating their palm to change perspective, and bringing it closer for a closer inspection. This localised view could be placed beside a monitor for reference and dismissed at the snap of the fingers. It could also be used as a collaborative tool for controllers to share information about interesting areas of the airspace or hand over a situation to another controller.

B. AR Magnifying glass

The AR Magnifying Glass is a prototype display technique for smoothing interactions between the physical and the information space. By moving the "lens" over parts of the 2D radar screen, it will “magnify” those parts of the screen. Instead of magnification, the lens could display a 3D representation, additional text, or anything else that computers can normally display. Figure 4 shows a picture of the AR magnifying glass, implemented in the ARToolkit, using a cardboard frame.

The lens is envisaged be a physical tool that will be permanently attached to the screen. When a user needs additional information the tool will be grabbed, dragged to the relevant area and used to acquire the necessary information. When the information has been obtained, the tool is released and springs out of the way. This tool would greatly reduce the intrusiveness of acquiring additional information.

Figure 4. AR magnifying glass, implemented using the ARToolkit and cardboard.

C. AR 3D Wall View for Stack Management

The 3D Wall View (also referred to as the AR Stack Manager), is a combination of the 3D Local View and the Precision View. The 3D view allows a rapid comprehension of the structure of the airspace, while the vertically-oriented gradation on the wall (called the ‘altitude ruler’), gives users precise data needed to assess the traffic situation or guide aircraft accurately. Such a view can allow a controller to check whether a given aircraft is able to level off at an assigned flight level after a climb (or descent); visualize the 3D path of an aircraft close to terrains; monitor one or more holding stacks at the same time, or access a pilot’s point of view during severe weather conditions. All these airspace features can be included and magnified in a sub volume such as the one described above.

T T

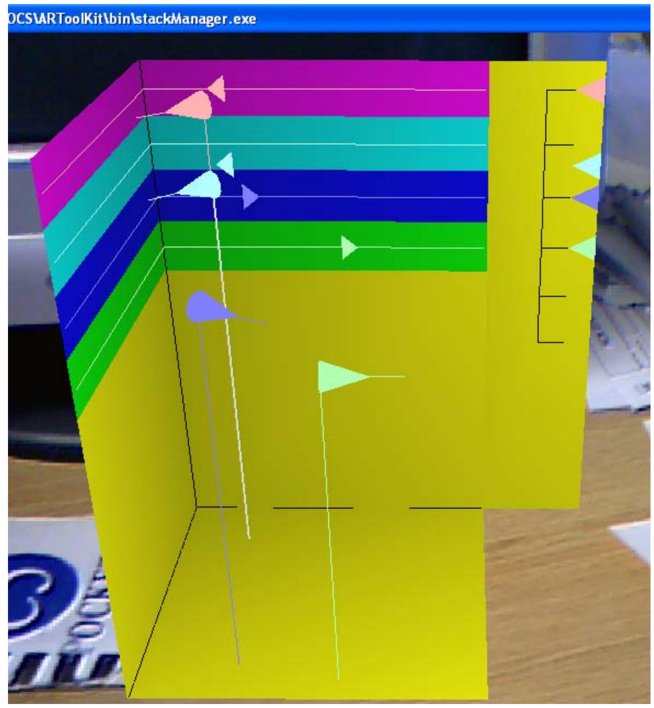

Figure 5. The 3D Wall View with the ‘altitude ruler’ allows altitudes projected on the walls to be read accurately.

D. AR 3D Wall View for Approach Control

The AR 3D Wall View for Approach Control is another example of combining the 3D Local View with the Precision View. When aircraft carry out complex approaches, it is easier to use a 3D visualisation to gain an overall understanding. When directing traffic, however, the precise 2D information visible on the walls is most useful in that it provides a good spatial representation of the selected traffic situation, providing traffic direction and positions. Most importantly, the Wall provides better distance assessment than pure 3D.

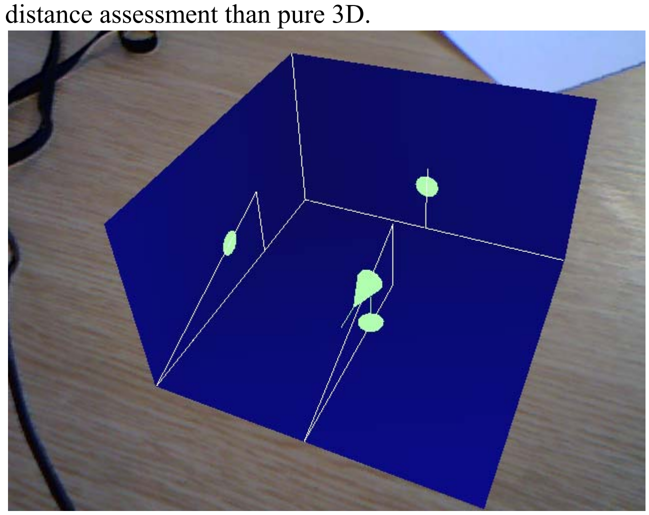

Figure 6. AR 3D Wall View for Approach Control.

E. Skyscraper and Symbicons

The skyscraper set of display concepts described here were developed from an earlier design we called, "stereoscopic displays" (see report D1.2 that reported on the full set of concepts) that allowed a controller to monitor a standard 2D plan view and to "dive" into it when needed by activating the stereoscopic visualisation. Having 3D throughout was not useful as it still presented the same problems of 3D visualisation. We therefore developed, the concept of stereoscopic perspectives for localised or selected areas of the 2D space. This developed into the skyscraper view concept.

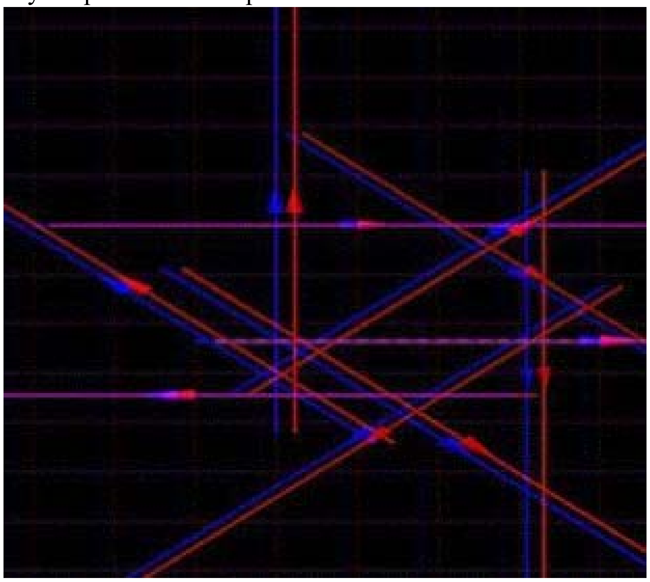

Figure 7. The stereoscopic display.

The Skyscraper display allows us to see a 3D representation of an area of interest within a 2D overview of the entire airspace. The aircraft in our concept prototype are represented as red-cyan anaglyphs in the selected airspace. When viewed using red-cyan filters (cheap 3D glasses), the selected aircraft appear to stand out of the display, much as if one were looking down at skyscrapers from above. Aircraft at higher altitudes appear closer to the viewer while aircraft at lower altitudes appear farther away from the viewer (Figure 6). Such a 3D-in-2D view is useful for decluttering since the selected aircraft appear to stand out of the display, gives a controller a quick assessment of the traffic situation, and can provide clear indications of where the aircraft are in 3D space. Note that such a view can be combined in the "AR magnifying glass" lens view, and can be implemented in advanced multi-layered display technology that does not require glasses or anaglyphs to simulate visual depth.

Symbicons, or icon with embed symbolic 3D-related information can be used to add information about the aircraft's behaviour, indicating if the aircraft is climbing, descending or banking (see Figure 9).

This symbicon concept has been implemented as a short black line on the axis of the aircraft. If the line is towards the rear of the aircraft (triangle) symbol, it indicates that the aircraft is climbing; and if it is located more forward, it indicates it is descending. If the line is to the left, it indicates that the aircraft is banking left, in a climbing left turn (if to the rear and left), or in a descending left turn (if to the left and forward).

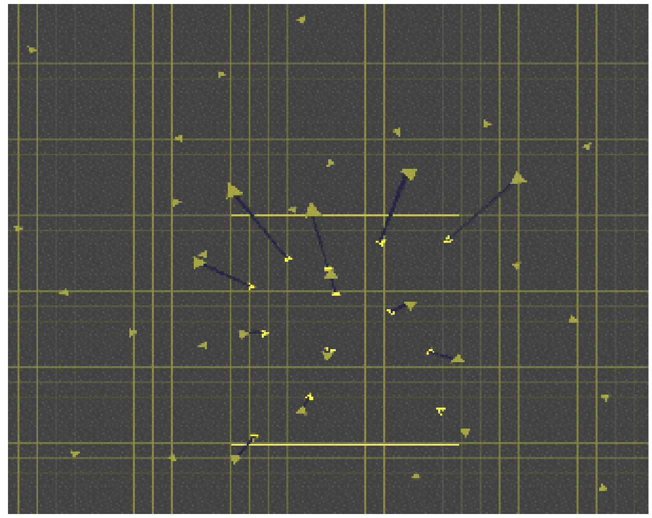

Figure 8. Skyscraper display, showing aircraft in selected area appear as skyscrapers looking down from above. The red-cyan anaglyphs appear as 3D imagery when viewed through red-cyan filter glasses.

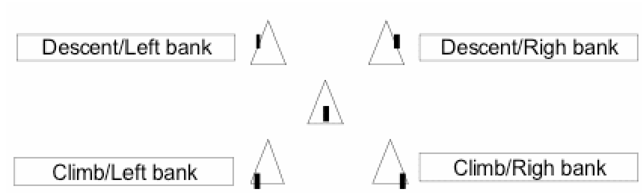

Figure 9. How the symbicon representation works.

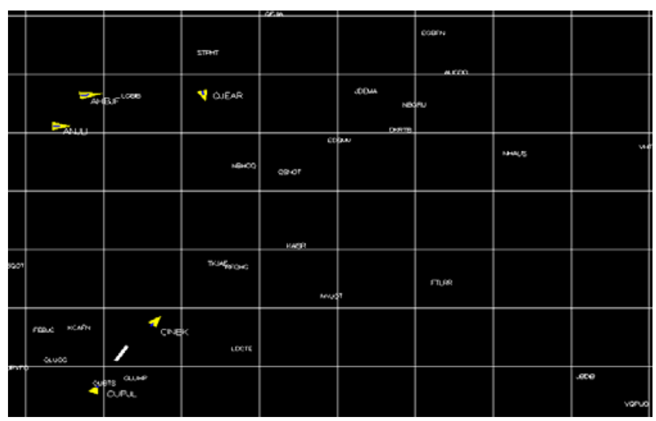

Figure 10. Symbicons display combines 3D information such as climbing, descending, banking data symbolically.

Symbicons and the 3D skyscrapers are complementary technologies. By combining them, users can readily perceive information about the intentions and actions of aircraft, and rapidly determine flight levels. In this design, we can preserve the need for global awareness of the overall traffic situation that comes from the 2D representation, declutter the display by separating the aircraft and their labels in depth, and support analogical reasoning. Smallman and colleagues [10, 16] found that symbolic 3D led to better visual identification performance.

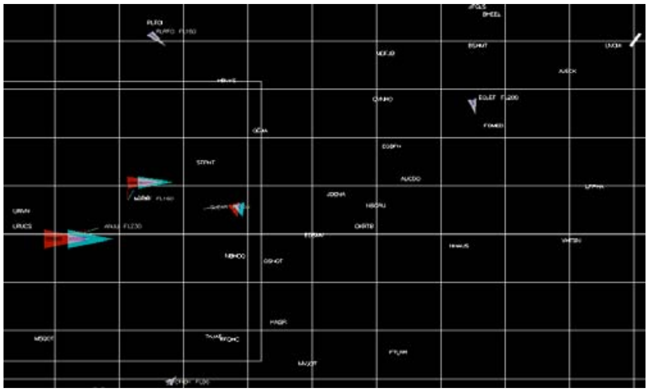

Figure 11. Combined skyscraper and symbicons display.

F. *Table Top Display*

The Table Top Display is a collaborative workspace rendered in genuine 3D. Multiple controllers can view a single workspace from multiple directions, allowing them to share ideas and solve complex problems. The view allows examination from any angle, and can provide textual information, just like a 2D display.

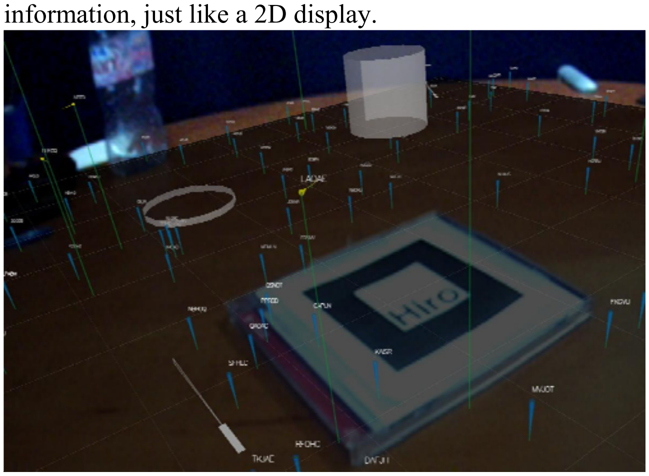

Figure 12. Table top display that can be shared by several cooperating controllers.

Note that we are able to augment the entire table top - we are not limited by the size of the marker. In such a display, we can embed different “tools” such as the 3D wall with the altitude ruler to assess aircraft altitude in a selected part of the airspace. Figure 13 is an early paper mock-up of how the 3D walls could be implemented on the Tabletop display.

III. Investigating the Capabilities of the Innovative Concepts

The objective of this phase was to identify the capabilities afforded by the new 3D/2D representation concepts and their potential uses. In particular, to identify the variety of perceptual and interactional issues that may arise, such as the new capabilities that the proposed display concepts enable a controller to perform. Also of interest was the identification of feature interaction effects, i.e. how some

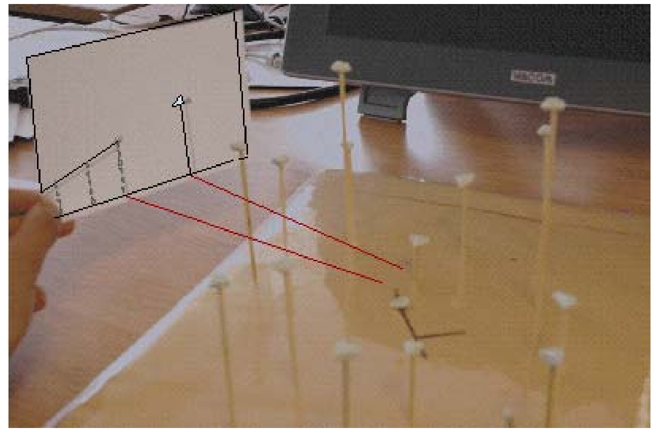

Figure 13. Early paper mock-up illustrating how the 3D Wall View display can be used in a 3D space to provide precise altitude information.

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concepts might in combination lead to more powerful capabilities, or hinder controller performance. It was not the intention of the evaluation to assess how much, how fast, or how accurately the new designs would enable a controller to perform a particular set of operational tasks. Although mindful of the operational context and the importance of a human-centered approach, the concepts were still at an early stage in the technology research and innovation process, and therefore too immature for operational evaluation. A more quantitative evaluation at this stage would be premature, and would have instead hampered the exploration of their full capabilities

The evaluation took place at EUROCONTROL with three non-operational Air Traffic Controllers, each with between 3 to 18 years of operational experience. We asked them to perform an exploratory tasks: each participant was presented with simplified scenario demos, and asked them to imagine how the new visualization could help them to carry out the operational task. We also used a set of predefined questions to stimulate thinking.

A. *Applications of the 3D-in-2D Concepts in ATC*

The study showed in general, that 3D visualization can help a controller manage holding stacks; busy airspaces sector; and military aircraft interception.

For these applications, 3D in combination with 2D appear to offer the potential to reveal 3D positions and trajectories relative to each other. It can also show the dynamic and static 3D volumetric shapes of restricted airspaces, thus reducing the cognitive load. The holding stack was felt to be an application area that could benefit significantly from 3D, due for instance, to current difficulties such as overlapping aircraft in the same 2D space at different flight levels engaged in the holding pattern. This make holding stack a candidate for further investigations of 2D and 3D in the next phase of the project.

As regard busy airspace sector, 3D could be useful for disambiguating traffic arriving or departing from a given airport from those arriving and departing from another nearby airport. This point is particular important looking at technologies such as PRNAV (Precision Navigation), which could possibly increase the effective use of the airspace. Aircraft could be instructed along a 3D path not available today due to uncertainty in navigation (perhaps underneath another flight path?), and viewed with symbicon representations using a local AR perspective. For instance in between the departure of a fast and a slow aircraft - the former departing first and climbing at higher altitude, the latter departing shortly afterwards and climbing at a lower altitude - it is not possible to put any aircraft today; but with the support of PRNAV it would. Such an improved use of the airspace would result in higher density of activities which could be better appreciated in combination with a 3D visualization.

The use of 3D can provide military controllers assistance to track high performance aircraft. This supports the finding of a previous work analysis (Amaldi, Fields, Rozzi, Woodward, & Wong, 2005). At this stage however it seems that more operational evidence need to be collected, since none of the subjects involved in the session had experience has military experience.

B. *Applications of 3D-in-2D Concepts beyond ATC*

Other application areas beyond ATC include airspace planning; procedure design, experimental scenario design, and training.

Just as 3D CAD (Computer Aided Design) applications support engineers to explore construction sites with a combination of both two dimensional and three dimensional views, 3D could enhance planning and design activities since it would enable airspace planners and procedure designers to explore in 3D the airspace, collect a qualitative understanding for instance of noise distribution, leaving the operator the possibility to refer to 2D to carry out precise distance estimations, e.g. among planned procedures.

The same applies for instance during Experimental Scenario Design. For instance during the preparation of a given holding scenario, a psychologist could: (i) visualize in 3D traffic in correspondence of the holding to control how the trajectories he has designed look like; (ii) observe traffic evolution in time by sliding back and forward a timeline; and (iii) modify if needed aircraft position at any given time. This control of scenario geometry and dynamics would save the experimenter the relevant mental effort needed to a reconstruct scenario conditions in his or her head, thus fasting and make the process more accurate.

Training could potentially be another application of the 3D-in-2D display concepts. A trainee could interactively explore a localised 3D space using different features to understand its configuration, the distribution of global traffic, and assess the implication that his or her intended maneuver would produce, e.g. lack of separation, or overshoot.

IV. The Human-Centered Innovation Process

The development process adopted in Year 1 for the 3D-in-2D display project heavily emphasised a human-centered innovation approach. We did not use a standard engineering development process, where the focus of user discussions would be to define and refine a small number of solutions. Instead, we focused on creatively generating and expanding the number of new ideas that were based on a sound understanding of the user, the work, and the work domain, and hence the nature of the tasks and the goals and user expectations. This understanding of the controller's cognitive tasks and strategies, were based on work analyses carried out in the recently completed FP6-funded AD4 Virtual Airspace Management project.

Our efforts aims at producing radically new yet meaningful display designs by orchestrating powerful innovation methodologies such as De Bono's Lateral Thinking techniques [30], and Wei & Yi-wen's Combination technique [34], with Human Factors methods in order to consider both the "blunt end" and "sharp end" of the system, and taking into account user work practices, during the innovation process. In our approach, we systematized the creative and generative activities by a structured process comprising three iterative cycles which alternate systematically between creation, technology development (prototyping) and (review) phases.

A. *The Problem of Innovation*

To innovate we needed to address two key challenges: (i) To achieve a significant change in the perspective that we – investigators and operators – viewed current ATC display designs, and (ii) while ensuring than proposed solutions will be meaningful and can be used from an operators' standpoint.

The first point arises because of the basic scope of the project. 2D Plan Position Indicator (PPI) radar display designs has not changed significantly it was introduced 50-odd years ago. Thus is it is necessary to look at radically new visual display techniques that can enhance safety and increase the capacity of the ATC system anticipated over the next 20 years, especially from needs arising from possible new operational concepts that will be developed through SESAR in Europe and NGATS in North America. This requires a new approach that would allow us to progress extensively from the current ATC system, since designing for the current system would have only resulted in marginal improvement of what is already available. We did not want to "design for the last war". For this reason our approach largely emphasized systematic creativity to achieve a significant shift in the perspective with which we considered ATC practices and in particular at current information visualization systems in ATC.

Also, achieving radical innovation means knowing not only the current situation – how activities are carried out today, but to makes sure that the tools designed are meaningful for the ATC community in the future. For this reason our project has been informed by a solid review of current ATC practice knowledge. We reviewed the visual requirements and ENCA (Expectations, Needs, Constraints, Assumptions), and analysed them from both the blunt (such as organisational policies) and the sharp end (operator strategies), some of which were based on previously collected data during the AD4 project [31, 32]. In addition to that, our review of current innovative visualizations summarised in the Combination Display Framework described earlier on, informed us about existing opportunities for innovations. This knowledge enable us to initiate the Innovative Creation process.

B. *The Innovative Creation Process*

This process comprises three iterative cycles which alternate systematic idea and concept creation, technology development (prototyping) and review phases.

1) Cycle 1. Innovation Initiation – Perspective change

Objective of his phase is to instill a innovative perspective among the project team members and users. In our three focus group sessions called creativity workshops, the focus was to produce a large number of "provocative ideas" that required participants to generate radically different ways to do work today in ATC. Such ideas challenge various areas of established ATC practices, such as work organization, e.g. "controller s can work from home"; to visualization, e.g. "The display appears on the control room floor and controllers can walk over it and interact with (virtual) 3D pipes, corresponding to aircraft 3D trajectories". At this stage, implementation was not an issue as long as the provocative ideas challenged existing assumptions and instilled radically different – out of the box – design perspective fundamental to initiate effectively innovative thinking. Their systematic production and collection took place during the three creativity workshops based on De Bono's [30] lateral thinking methods.

Our creativity workshops involved postgraduate students of product design and human-computer interaction, and human factors and visual perception experts, provided us with the necessary level of creativity and theory, while the involvement of ATC experts such as controllers and ATC managers, made it possible to assess the usefulness of the ideas and to distil from this set of provocations, those that were radically new from the ordinary.

2) Cycle 2. Display Concept Innovation

The Innovative Concepts were then developed, using the provocative ideas identified in the earlier cycle as source of inspiration, and the Combination Display Framework to systematically identify gaps of opportunities in the framework. The Innovative Concepts devised during this cycle, should be considered as visual and interactional elements: They do not represent a complete system yet, where each innovative concept would be combined with other concepts into a more complete radar display or toolset. At this stage the ideas and concepts were not anticipated to allow the user to control traffic. At this stage focus is to understand the capabilities offered by each Innovative Concept. In the next step in this cycle, we then assess the ways that they can combine into a more complete radar display or toolset later on in the process.

The "assessment" in this cycle consisted of what we called the *Capability Investigation*. This qualitative evaluation focused on understanding capabilities of the concepts, how they can be combined and extended, rather than measuring the controller's performance if they were to use it. In fact measuring human performance in this phase would be not possible since the prototypes were not ready to sustain an operational task. However, it allowed us to discover what meaning the user associated with the concepts. Such qualitative investigations are needed firstly to minimize the risk of overlooking potential innovations [33] and avoid premature rejection without having a thorough understanding of the concept potential. For example, drawing on a more common experience, applications designed in early (c. 1989) version of Windows version required the user to type menu selections into a command line interface, despite the fact that the GUI (Graphical User Interface) system could accommodate drop-down menu selection. At that time, the opportunities for innovation offered by the drop-down menu were overlooked, possibly due to a lack of a maturity in understanding what the GUI could offer.

Secondly investigating the capabilities allows distinguishing relevant aspects of the concept relevant from a user perspective. For example one of the learning is the "3D AR in Your Hand" display can be considered from a controller both as (i) Visual Container – which refers to the capability of the concept to hold any kind of information in different positions in relation to the user; and (ii) Information Visualization, which consist in the information which is being visualized. Such distinction was not evident to us prior the capability investigation phase.

3) Cycle 3. Display Design and Evaluation

The objective of this phase is to bring the Innovative Concepts together and to combine them into fewer but more complete display designs or toolsets, i.e. they will be complete enough to convey to the user the HMI concept and more specifically how it might support him or her it carrying out an operational task. Combination is a technique in the innovation process that consists of combining and re-combining elements to obtain a better product [34]. Although this cycle was supposed to start in Year 2, we have already initiated some of these combinations, e.g. (i) the combined Skyscraper + Symbicons view, and (ii) the combined 3D wall view with the 2D precision (ruler) view, provide two examples of potentially successful combinations.

Assessment of the combined displays is scheduled to take place in Year 2, and will emphasise the assessment of operational usability. These combined prototype designs will be developed and evaluated in order to asses their usability in laboratory-based operational scenarios, by mean of well know methods such as expert reviews, usability tests and lab experiments.

With this process we proceduralised the concept design phase. Designing a process informed by ATC practioners and at the same time integrating creativity tool s to generate systematically innovative ideas. Table 2 summarises the process and differences between the artefacts at their different stages of development within our human-centered innovation process.

TABLE 3
DIFFERENCE AMONG THE OUT PUT OF THE HUMAN-CENTERED INNOVATION PROCESS.

	Innovative ideas	**Innovative Concepts**	**Displays**
What	Basic Element. Abstract ideas of Individual feature or Complete system	Interactional Unit. Innovative concepts correspond to features of a complete HMI. Controller can carry out only small part of the operational task.	
Implementation	Implementation is not an issue Idea is documented on paper either as a sketch or text only	An early low fidelity prototype is available. The idea is quickly prototype to convey the concept to the controller	Complete HMI. The user can carry out the operational task.
Technology	Technology at this stage is considered as an opportunity	Technology as enabler, the best technology to generate the cheapest technology to prototype an idea	
Generation Innovation technique	Creativity Workshops	Visual design, Rapid Prototyping and Refinement	Combination
Evaluation	Uniqueness of the ideas	Capabilities of the innovative concepts	Operational Usability

V. THE SIMPLIFIED ATC SIMULATOR

As part of the 3D-in-2D project, a software infrastructure has been developed to enable the project investigators to easily create dynamic air traffic scenarios and use them to test the different 3D/2D HMI concept prototypes emerged during the project.

The project team chose to develop such a platform with the aim of having an easy to use tool for creating relatively simple air traffic scenarios for HMI testing purposes, with special emphasis on evaluation (at least for Year 1 of the project) of visuo-spatial aspects and expected benefits of highly innovative 3D-in-2D HMI concepts. For this reason, simplicity and ease of use have been considered as important points.

While other existing, more sophisticated platforms (such as AD4, ESCAPE, eDEP) would have provided the possibility of creating much more realistic ATC simulation scenarios, such complexity and realism was been found to be beyond the scope of the early phases of the project, where the focus is more on generation and evaluation of many highly innovative HMI aspects rather than on carrying out operationally realistic types of assessment.

A. Overview of the ATC Simulator

The Experimental Test bed consists of: (i) an editing tool, provided with an intuitive graphical interface, which supports the creation and editing of simple ATC scenarios, and, (ii) a simulation environment (simulation engine) capable to run the scenarios and to interface to the different 3D-in-2D HMI prototypes, feeding them with (near) real-time traffic data.

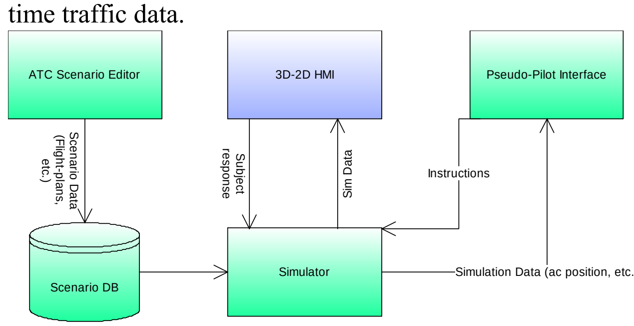

Figure 14. Test bed architecture.

An additional pseudo-pilot interface module has been foreseen in the overall test bed architecture, allowing an operator playing the role of pilot to modify airplanes behaviour in real-time during the scenario simulation. The implementation of such module, however, has been planned for subsequent phases of the project (Year 2), as such feature was not necessary in the early evaluation of the concepts. The following figure provides an overview of the test bed architecture, showing the different modules and the major data flows between them.

A. Capabilities

The system supports the scenario design process by means of a graphical user interface which allows the user to easily create basic ATC elements, such as fixes, waypoints, weather elements, and to define flight plans.

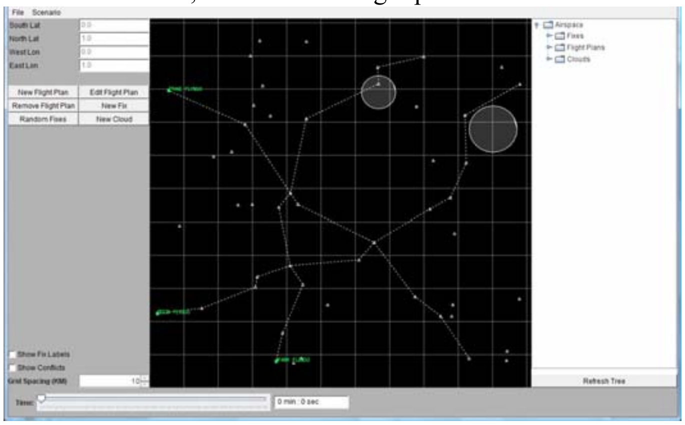

Figure 15. HMI of the simulator editor

The ATC editing environment supports a number of capabilities, allowing the user to:

- specify a geographic region containing the airspace of the scenario under creation;
- create a set of waypoints ("fixes");
- create aircraft flight plans, specifying information like the trajectory, the start time of the flight, the flight levels and the speed at which the aircraft will fly;
- create simple weather objects (e.g. representing cumulonimbi) defined as 3D volumes;
- verify the presence of potential events in the scenario, such as conflicts between airplanes (loss of separation) or airplanes crossing a weather object;
- play / preview the scenario in 2D
- insert textual comments and other auxiliary information for each scenario.

The created scenarios can be then performed by the ATC simulator, which generates the data of flying airplanes according to the flight plans specified in the scenarios, and dispatches those data to the HMI concept prototypes that are connected to it. The data transmission from the ATC simulator to the HMI prototypes is realized by server-client communication scheme, based on the TCP-IP protocol, in which the simulator acts as a server, while the HMIs act as clients.

VI. Conclusion and Lessons Learnt

As we review the work we have done and accomplishments of Year 1, a number of issues were reflected upon, and a number of lessons were learnt. These are discussed next.

A. Expectations, familiarity, and the Task-Artefact Cycle.

Radar displays have progressed through two main design concepts since they were first invented and deployed over 60 years ago during the Second World War. The early displays were oscilloscope-style presentations of aircraft, showing the strength of the radar signal returns indicated distance in a particular direction, and the current 2D plan position indicator style displays with 'blips' showing the location of aircraft in a plan view perspective. Altitude information was initially added through specialised height finding radars, and now through improved radar and SSR technology. This altitude information is then mentally integrated by the controllers to create dynamic 3D mental models of the traffic situations, a spatial expertise that often takes a controller several years to develop. Many air traffic controllers have been trained to create and maintain this dynamic mental 'picture' [35]) of the air traffic situation, developing heuristics and strategies for keeping that picture current and for 'looking ahead' in order to anticipate problem situations and to de-conflict traffic, and techniques for disambiguating information presented on the 2D radar PPI. For example (from personal experience whilst the first author was working in the Repulbic of Singapore Air Force during the introduction of a digital radar system in the 1980s by the Civil Aviation Authority of Singapore), the trail of blips left by an aircraft – their direction and distances apart – on the phosphor CRT of the older analog radars, provided cues about the direction and the speed with which an aircraft was traveling. Having been trained to interpret such cues, the controllers found it very difficult to transition to the modern digital signal displays that did not provide the trail of fading blips when they were first introduced. The radar engineers had to subsequently program in the trail of blips, despite providing heading and speed vectors attached to the digital blips.

Considering the severity of consequences of aircraft accidents, air traffic controllers tend to be conservative, preferring to work with the familiar or with artefacts that satisfied their expectations. It is against this strong background of experience and prior expectations that we conducted initial evaluations of the viability of design concepts that were radically different from which they were familiar, and that behaved in ways that they were not trained to expect. Additionally, the procedures and the operating concepts for controlling, separating and sequencing of aircraft were developed based on a 2D perspective to ensure safe and expedient passage.

As innovation researchers, this was a significant realisation: While some of the negative feedback from the early evaluations of our concepts are valid, others have to be interpreted within this context. Some of the designs simply would not be appropriate for use to perform the tasks as they are currently practised. These new designs do however, open up new possibilities for new operating concepts and new ways of controlling aircraft. This is very much in line with the well-known Task-Artefact Cycle [36], which explains that new technology can change the way we work by offering new possibilities, and as we change the way we work, creates new demands or requirements. In other words, new innovations need to be used, practised with, in order for the user to understand what new possibilities it affords and therefore how their work can be changed or improved.

This has implications for the way we conduct future evaluations, especially if evaluating the operational usability of 'first-of-a-kind' artefacts at their conceptual states. There will be an incompatibility between the users' expectations and the assumptions that underlie their work, with that of the new designs.

B. Good ideas, poor implementation.

Designs should not be considered as a "single entity". A design has several dimensions, and their success depends very much upon the compatibility among these dimensions. Good ideas can easily be discounted as a bad idea due to poor implementation. Poor implementation occurs for a variety of reasons, including poor software programming, lack of attention to design issues, poor translation of the idea into the artefact, or an over sight of how the artefact might be used. As we in the software industry are well aware, the functional requirements of a system can be implemented in as many different ways as there are programmers. What makes a difference is how the look and feel of the same functional requirements are rendered, e.g. buttons vs pop-up boxes, type-ahead vs select from a menu. These problems are made worse when developing in a new medium, as is the case in our project, developing to introduce 3D view information within the context of 2D space. How do they interact? how should the boundaries between the two spaces interface? The effect that the software coding needs to achieve can be coded once we can clearly articulate what the design needs to look like and hence how it should be rendered. This process can only come through a process of envisioning coupled with rapid concept prototyping, to rapidly visualise and to explore how these concepts work, and therefore could work. This is an essential step in the innovation research process: starting from an assumption that we have an understanding of the task, we need to create as many concepts as possible, exploring the various ways and combinations of ways that the basic requirement or principle of design can be implemented. We should at this stage be emphasising a 'what-if' approach to design to explore, extend and invent the design space, rather than developing just one or a small number of alternatives to perfection as we would when focusing on a final solution as is typical within the context of standard software engineering projects. Innovation requires variety and many design sketches [37] to nurture and develop the ideas. We should refrain from developing early radical ideas into high-fidelity engineering prototypes early in the innovation process. For this reason, we adopted technologies such as the Augmented Reality AR Toolkit to enable us to rapidly construct many concept prototypes as quickly as possible so that we could explore their capabilities and to demonstrate the ideas. Through this we realised the possibilities that the ideas afford.

C. Concept maturity.

Another issue that became a significant point of contention was the compatibility between the designers' and intended users' understanding of the maturity of the concept, i.e. how ready is the concept for deployment. It became clear early during the project from the controllers' comments that their time horizon was in the 5 years ahead timeframe. This is a normal expectation for standard technology implementations. However, innovations we were referring to were necessarily much less mature than that. We were referring to a 10 to 15 year deployment timeframe due to the changes needed in operational concepts as well as having the necessary technologies in place (e.g. downlink of aircraft attitude information). We found the NASA Technology Readiness Level (TRL) framework a useful concept for providing a common frame of reference to discuss the concepts in relation to the users' expectations. A TRL Level 1 and 2 refer to blue skies test of concepts and principles and early feasibility studies, and this is where the 3D-2D display concepts are presently at, and Level 8 and 9 refer to the technology as being deployable, i.e. "mission qualified" and "mission proven". As a result, we were later able to discuss what *could* the designs be use for, rather than simply, is it usable at this stage for carrying out a series of validated ATC tasks. In innovation research, one of the key goals is to identify and open up new possibilities which can later be turned into engineering solutions. Sharing this common frame of reference with management in the funding body is also important as it influences the expectation of when candidate concepts need to be selected, and the expectations from subsequent evaluations. As a final example of the length of time it takes for ideas to mature: Microsoft's 2007 Vista operating system desktop concepts of perspective and different spaces for different purposes, can be traced back, for example, to concepts, some of which were published over10 years ago. These ideas include the information forager and web-book ([38]), perspective displays (summarised in [39]), and the data mountain [40].

D. Features vs solution.

As we further developed the ideas during the innovation process, and as we discussed the ideas with various groups of people, including the controllers, we realised that it was critical to distinguish between features (the elements that would be later combined to create a whole interface), and a complete interface solution. Some of the designs are intended to be part of a larger tool set, rather than used in a stand-alone way. For example, the 3D wall display showing an accurate altitude measuring "ruler", although presented as if to be viewed on the side of one's desk, should be seen as a feature or element that is to be combined, with say, the AR 'magnifying' glass display, such that it provides the wall view in the AR 'magnifying' glass viewing portal. This combined view can also be further combined with the AR-in-your-hand view, allowing you to select and pull off the display, a magnified, walled view of the selected airspace with the altitude ruler, in your hand. As stand-alone concepts, the ideas that we propose would in all probability fare poorly, just as a drop-down menu, a single element of a Graphical User Interface, in isolation from the rest of the GUI. Combining these elements into a practical tool set will be the focus of efforts in Year 2 of the programme.

E. Visualisation and interaction

Another key distinction about the designs is the differentiation between the container and its content. This fundamental concept allows us to create new combinations, matching content, what we would like to view about the traffic situation, with appropriate or novel ways of accessing, manipulating and controlling what is viewed. For example, the 3D wall concept, shows aircraft in 3D space, with their 'shadow' projected against a vertical backdrop of two adjacent vertical walls. The walls could be augmented with precise altitude measurements to enable easy reading of the aircraft's altitude, position and altitude in relation to the other aircraft to support very quick at a glance assessment. Employing this in a table-top display in combination with, say the AR 'magnifying glass' container allows us to magnify (or execute other manipulations) a selected area of the airspace and traffic situation, in place. Then if the controller wants to pick it up for closer examination, the AR-in-your-hand container can be used to select this portion of the airspace and have it brought closer to himself, or hand over that situation to another controller cooperating with him at the table-top display. Crucially, thinking about contents and containers in this way, allowed us to think beyond 3D views of data. By decoupling how we manipulate the content, from the content itself, allowed us to consider other forms of data representations. Such representations of content included the notion of symbicons, or the representation of aircraft information symbolically as icons. Thus, not just representing an object, say, an aircraft as a triangular icon, but by incorporating appropriate symbologies, we can show that the aircraft is climbing or descending, or banking left or right. Combining, for example, the AR magnifying glass method of manipulation, we can select an area to show the symbicons projecting out of the 2D display in a 3D skyscraper display view, with the symbicons of the aircraft that are higher appear larger and closer to the viewer (when say, viewed through red-blue 3D glasses), than those aircraft that are lower and hence appear smaller and further away, in the same field of view. Thus, this separation of contents from containers will allow us to create hybrid displays by enabling different ways of combining the contents with the containers.

F. The Simplified ATC Simulator.

In early discussions, we were faced with the decision of adopting more advance and realistic simulators, rather than for the project to re-create the wheel, and develop a simulator that would have much less capabilities than existing ones such as ESCAPE or eDEP, which has fully validated operational scenarios. However, more time would have been needed to adapt these more sophisticated platforms for our much simpler purposes: to provide a simple ATC simulation system that could generate aircraft tracks in order that we will be able to see how the various design concepts would appear. In addition, we were intending that the simple ATC simulator can be used as an experimental test-bed, allowing the capture of user response time and track how the user directed the aircraft under his or her control using the different design concepts, with the intention of studying the use of the novel interfaces. Because this test-bed was developed within the project, it proved to be much easier and quicker for us to connect our design concepts and to evaluate the visualisations, which allowed us to make design refinements rapidly.

G. The process of innovation.

Although not explicitly mentioned in the reports on this project, we did not start the technology innovation without some prior understanding of the human in the work domain. In a prior FP6 project (AD4 Virtual Airspace Management), we had completed a number of field observations and cogntive task analysis of controllers' decision making, coordination and information representation needs. Using this and other reports in the literature on controller behaviours, we developed the new innovations. While having a human-centered perspective is crucial to design tools that work for the human operators, we also realised that this crucial need to be informed by an understanding of the current work practices, can in itself hinder researchers from making dramatic advances. Focusing on work practices can be retrospective. The practices exist, and is what the operators do. Designing new systems for compatibility with current work practices is like designing new weapons to fight the last war, instead of designing new ways to win a new war that could be fought differently from the last war. Pure technology development can, on the other hand, have little to do with addressing the needs or nuances of the work domain, focusing instead on establishing capability, and little on how the human could use it. We can call this the 'because we can' approach. For technology innovation to succeed, the innovations need to be human-centered. We need to take into account human work and work practices, and using creativity techniques to challenge accepted practices, creatively consider how the new technology will enable new possibilities as we re-engineer the processes, and then ascertaining the technology's usefulness, through both technology-oriented and use-oriented evaluations.

H. Industrialisation.

Through our industrialisation reviews, it became apparent that the notion of 'industrialisation' needed to be defined. Did it mean the development of a product to a stage where it would be ready to be sold to the world at the end of the three years? (i.e. TRL Level 9 "mission proven"; or did it mean that the 3D-2D displays can be implemented as a prototype and demonstrated in an operational environment? (i.e. TRL Level 7); or implementation as System /subsystem /component validation in a relevant environment? (i.e. TRL Level 5). Setting these expectations is important so that funders and researchers are not talking at odds with one another. As a project team, we believe the realistic expectations are TRL 4 where component or subsystem are validated within a laboratory environment. The components are implemented as standalone prototypes tested, and then with integration of technology elements, and with experiments conducted with full-scale problems or data sets such as those validated operational ATC scenarios in EUROCONTROL's eDEP ATC simulator.

Increased work package that would develop and extend from the technologies developed during the earlier successful FP6-funded AD4 platform.

I. The way ahead.

As we leave the creative-emphasis Year 1 of the project, our strategy for progressing the work in Year 2 (2008), will be to focus on validating and bringing the technology closer to being deployable in operationally valid ATM laboratory settings. We will:

(a) consolidate, combine and refine the candidate concepts into candidate interface solutions,
(b) create an alternative operational concept and a mock-up context of use which have alternative airspace designs and traffic situations that are not based on 2D constraints, so that the use of the innovations are not limited by the force of habit and past experience,
(c) conduct evaluations that will be directed at assessing operational usability issues within alternative operational contexts,
(d) investigate alternative technologies to the augmented reality AR Toolkit, and to define an migration path, to a more "industrial strength" platform that could integrate with industry standard platforms such as ESCAPE and ATRES. Drawing from previous work funded through FP6, the AD4 Virtual Airspace Management platform,
(e) initiate the search for an engineering solution.
(f) add the pseudo-pilot and other functions to the Simple ATC Simulator and Experimentation Test-bed, and to develop according to the road map defined in our deliverables, and if funding permits, extend its architecture to be compliant with the simulation industry standard programming interfaces such as HLA or SMP2.

To be able to accommodate these activities, some of which are new, would benefit form additional funding support.

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The Co-ordinated Airport through Extreme Decoupling

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***Abstract*— This paper presents the results of the first year research in the EUROCONTROL CARE Innovative Research III project on 'The Co-ordinated Airport through Extreme Decoupling' (CAED). It is the objective of this research project to improve planning at airports by using a new methodology: extreme decoupling. In the first year of the CAED project, this innovative idea has been elaborated and developed into a mature decoupling model and working prototype. This model and prototype have been applied to the domain of ground handling, demonstrating that in this domain the pre-tactical planning based on decoupling can offer important advantages. These advantages will show up in the tactical phase, when disruptions necessitate re-planning of the original plan. In these cases, the decoupled local plans offered by the proposed new planning approach ensure that re-planning can be kept as local as possible – whilst guaranteeing that a solution does not conflict with other plans. This enables ground handlers to solve many tactical disruptions locally, thus drastically reducing the co-ordination overhead involved in negotiating with other parties. Given the large number of plan disruptions occurring daily at airports, and the increase expected in air traffic, such a planning tool seems to be a valuable asset.**

***Index Terms*—Ground Handling, Planning, Air Traffic, Modelling**

I. Introduction

IN 2004, EUROCONTROL predicted flight traffic in Europe to double by 2020 [7]. Given this increase in air traffic, airports will become a major bottleneck in the air transport system. Expansion of airports, however, is expensive and often impossible due to safety and environmental constraints. Therefore, airport authorities are seeking methods to increase airport capacity by making more efficient use of existing resources.

Currently, one of the most important factors preventing a more efficient use of resources is the occurrence of disruptions. At any medium to large size airport dozens of disturbances occur daily. Without re-planning, these disturbances may lead to grave consequences: flights delaying other flights (reactionary delays), provoking gate changes, affecting the in- or outbound capacity of the airport, or even hampering flights at neighbouring airports. Therefore, re-planning has become a daily necessity.

Given the complex and distributed nature of the airport domain, however, re-planning is not an easy task. It typically involves a large group of parties, each having their own (commercial) interests, resources, and planning constraints. Between these different parties, a large number of dependencies exist. For instance, between ground handlers, many temporal constraints apply (e.g., the fuelling company may not start fuelling unless all passengers have de-boarded). Any disruption typically affects a large number of activities, since any one activity forms part of a network of related activities (related temporally or by resources used). If a change occurs in one planning domain, it may have repercussions for all.

In particular, these complications have become visible in European Union projects such as LEONARDO [5]. Although fully acknowledging the distributed nature of the domain (by implementing a multi-agent system to support all actors), this project ran into difficulties when trying to model real-time scenarios. The majority of conflicts dealt with necessarily involved all parties. To solve any type of realistic disruption to the original plan, an enormous amount of communication was required to co-ordinate local planning functions. This led to a large co-ordination overhead when trying to solve the distributed planning problem. As a result, a general tool assisting all planners in solving real-time disturbances at airports turned out not to be feasible.

Airport planning is typically subdivided into a number of domains: arrival management, departure management, stand allocation management, taxi planning. In all of these areas, extensive research has been conducted to improve planning and assist planners by means of decision support tools (e.g., [5], [2], [4], [8]. Ground handling, denoting all processes that take place when an aircraft is at the stand[1] between flights, is

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[1] The term 'stand' will be used for both gates and remote stands throughout this paper.

a notable exception. Up until now, relatively little research has been conducted in this area.

This is surprising, since ground handling is recognized as a common and important source of delays in the air transport system. According to research conducted at London Gatwick Airport, ground handling services are the second largest contributor to flight delays, right after air traffic control (ATC) related delays. In this research, ground handling services proved to be responsible for 25 percent of all delays at London Gatwick [9];[10]. Ground handling delays typically lead to delays in other airport processes – not only for the delayed aircraft itself, but also for other aircraft, whether inbound, outbound or docked at other stands (knock-on delays). Thus, the performance of aircraft turnaround operations has a strong impact on the punctuality of the totality of airport operations. For this reason, NLR has recently – in parallel with the CAED project – intensified its research efforts on the turnaround process as a key chain in airport operations.

The CAED project presents a new planning approach to support airport authorities and local planners in the establishment of a robust *ground handling* plan for servicing scheduled aircraft. These services (e.g., boarding, fuelling, cleaning and baggage loading) are performed during turnaround: the process of servicing an aircraft at the stand between on- and off-block. Usually several agents are involved in this turnaround process, each performing a part of it.

The planning tool we present here assists planners in the establishment of a pre-tactical ground handling plan for a given day of operations. This plan is based on the flights an airline intends to perform, the airport's stand availability, and the various temporal and resource constraints to be obeyed for the ground services. Given this initial set of constraints, the planning tool creates a pre-tactical plan for each service provider involved in the turnaround. To this end, a method called temporal decoupling will be used to break up an initial stand plan into several sub-plans, which can be solved separately and merged again into a conflict-free pre-tactical plan. These sub-plans correspond to actions and constraints one single agent involved in the turnaround process has to complete. Temporal decoupling ensures that whatever plan execution scheme is applied by an individual agent, as long as it satisfies all local constraints, the feasibility of the total plan execution is guaranteed.

The tool's main advantage comes from its capability to support the solution of tactical or operational disruptions to this pre-tactical plan. In the tactical or operational phase, typically a number of disruptions will occur that threaten the pre-tactical plan. These disruptions need to be dealt with by re-planning part of the original plan. Of course, one does not want to make a new planning for all turnaround activities for that entire day. It is crucial to keep these re-planning activities as local as possible - affecting an absolute minimum of parties, aircraft, personnel, and resources. In current modes of operation, however, typically many parties will be involved in re-planning – leading to a large co-ordination overhead. In the plan created by the extreme decoupling tool, however, the original plan representation has already been distributed into independently constrained local plans. This enables parties to solve many tactical disruptions locally, thus drastically reducing the co-ordination overhead and saving time and money.

The first year of this research project consisted of (1) a literature survey on Simple Temporal Networks (STNs) and Temporal Decoupling, (2) the development of a turnaround model, and (3) the development of a prototype based on this model. This paper describes in brief all three research elements of the first year. Section 2 provides an overview of the literature study into STNs and Temporal Decoupling. Section 3 introduces the methodology and model that has been developed based on the theoretical foundation laid down in the study. Section 4 presents some of the results obtained with the prototype. Section 5 provides a discussion. Section 6 presents ideas for future research.

II. Literature Survey on Simple Temporal Networks and Temporal Decoupling

The Simple Temporal Problem formalism has proven to be very useful for the representation of and reasoning with temporal problems. After its introduction in 1991 [1], it has inspired many researchers to model temporal planning problems in a variety of practical domains.

In general, a problem is called a *temporal problem* when time constraints are involved. Examples of such temporal problems range from airport planning, crew scheduling, gate-assignment to trip planning, scheduling of meetings, etc. In particular, a *Simple Temporal Problem (STP),* like any constraint satisfaction problem, consists of a finite set $X = \{ x_0, \ldots, x_n \}$ of variables and a set of constraints $C = \{ c_{ij} \mid i, j \in \{0, \ldots, n\}\}$ between these variables.

A variable x_i is called a *time point variable* and represents a unique *event* that in an STP is characterized by its time of occurrence. Each variable x_i has to take a value in a fixed time domain T. A constraint c_{ij} relates two events x_i and x_j and indicates the allowed distances between the time points of the events represented by x_i and x_j. Every such a constraint c_{ij} is represented by a time interval $I_{ij} = [a_{ij}, b_{ij}]$ abbreviating the inequalities $a_{ij} \leq x_j - x_i \leq b_{ij}$ or the expression $x_j - x_i \in [a_{ij}, b_{ij}]$. Such a constraint expresses that x_j has to occur *at least* a_{ij} time units and *at most* b_{ij} time units after x_i.

The time point x_0 is a special time point, called the *temporal reference point*, that denotes an agreed-upon fixed point in time (for example, midnight UTC on 1 March 1963). Usually it is assigned the value 0. Therefore it is also called the *zero time-point variable*, and sometimes is referred to as z.
STPs can be used to model *temporal plans*. Such a temporal plan consists of a set of actions together with a set of

(temporal) action constraints. Action constraints might pertain to the start and ending point of one action *a*, thereby constraining the time it might take to execute the action, or might pertain to the start and ending points of two different actions.

When modelling a temporal plan as an STP, it suffices to take two time point variables for each action *a* in the plan: one variable represents the start of the action, and the other represents its end. Figure 1 below gives an example temporal network with three nodes x_1 to x_3 and the reference node, x_o. The edges correspond to the temporal constraints and are labeled with the minimum and maximum time (e.g., [0,150]) allowed to travel from one node to the other.

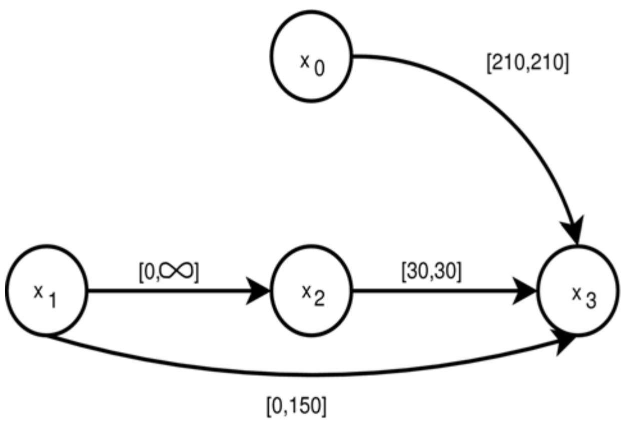

Fig. 1. A Simple Temporal Network.

In literature, a variety of algorithms exist to solve STNs in an efficient manner [1]. A solution of an STP is an assignment $x_i = \tau_i$ of values to all the time point variables $x_i \in X$ such that all constraints $c_{ij} \in C$ are satisfied.

Having explained the basics of Simple Temporal Networks, we now proceed to Temporal Decoupling. In a *z-partition*, the set of time point variables X is partitioned into two or more subsets x_1 .... x_n that all have only the zero time point variable z in common, and whose union constitutes the original set X. A temporal decoupling of the STN S = <X, C> is a set of consistent STNs $S_1 = \langle X_1 ;C_1\rangle,...,S_n = \langle X_{n,}, C_n\rangle$ such that $X_1...,X_n$ z-partition X, and any solutions for $S_1...;S_n$ may be merged to form a solution for the original STN S. In other words, temporal decoupling guarantees that even if each of the sub-STNs Si is solved completely independent from the other sub networks Sj, the simple union of the individual solutions constitutes a solution of the original network S.

In 2002, Hunsberger [3] developed an algorithm that given an STN S = <X, C> and a partitioning of X produces a temporal decoupling of S. For reasons of scope, only the global idea of the algorithm will be sketched here. Suppose that STN S is z-partitioned by S_X and S_Y. An edge in the distance graph representation is called an xy-edge, if it connects a time point x in S_X with a time point y in S_Y . If there exists a path from x to y through z, that has a length equal to or shorter than the length of the xy-edge itself, the xy-edge is said to be dominated by a path through zero and may be removed. The idea of Hunsberger's algorithm now is to add constraints c_{xz} and c_{yz} for each xy-edge, until all xy-edges are dominated by a path through zero, and thus have become redundant and may be removed.

III. DEVELOPMENT OF A TURNAROUND MODEL

In this section we describe the development of turnaround model based on the Simple Temporal Networks and Temporal Decoupling theory introduced in the previous section.

The airport turnaround process can be modelled as an STN. In this model, for each aircraft, a set of time point variables X can be defined that contains x_0, the in-block and o -block times, and the start and end times of all ground handling activities that have to be performed. The set of constraints C can be obtained by combining the temporal dependencies between activities with the norm times and minimal service times of all activities. The norm times specify the earliest start time and maximum duration of each activity. The minimal service times specify the minimum duration of the activities. For planning of all ground handling processes at the entire airport, a global STN can be constructed by combining all STNs of individual aircraft. The temporal reference point x0 (common to all individual STNs) can be used to link the networks.

The following example shows how this is done, and how the global STN can be decoupled into separate sub-STNs for each type of ground handling service. Imagine the following, simplified partition of an airline's stand plan:

- Aircraft X, KL310, type B737-300, Stand A17, in-block 12:00, off-block 13:15.
- Aircraft Y, LH200, type MD11, Stand A23, in-block 12:05, off-block 14:10.

Further, assume that just two ground handling services to be planned: fuelling and boarding. Based on the minimum service times, defined by the aircraft manufacturer, and the broader airline norm times, specifying start times and durations for each service, we can now define the temporal constraints. For aircraft X, a Boeing 737-300, these ground handling constraints could be:

- Turnaround: Start 12:00. Duration: between 38 (minimum) and 55 min (norm). Completed: between 15 min. (earliest) and 0 min. (latest) before off-block[2].
- Fuelling: Start 8 min. after in-block at the earliest. Duration: Between 10 and 37 min. Completed: between 18 min. (earliest) and 45 min. (latest) after in-block.
- Boarding: Start 32 min. after in-block at the earliest. Duration: between 5 and 18 min.

[2] This last constraint ensures that passengers will not have to wait longer than 15 minutes on board before the flight is initiated.

The same can be done for aircraft Y of type McDonnell Douglas. For this type of aircraft, larger than a Boeing 737-300, other service times apply:

- Turnaround: Start 12:05. Duration: between 51.4 and 120 min. Completed: between 15 min. (earliest) and 0 min. (latest) before off-block.
- Fuelling: Start 11 min. after in-block at the earliest. Duration: Between 16.6 and 59 min. Completed: between 28 min. (earliest) and 70 min. (latest) after in-block.
- Boarding: Start 80 min. after in-block at the earliest. Duration: between 16.2 and 36 min.

Given these variables and temporal constraints, the following STN can be constructed for flight KL310:

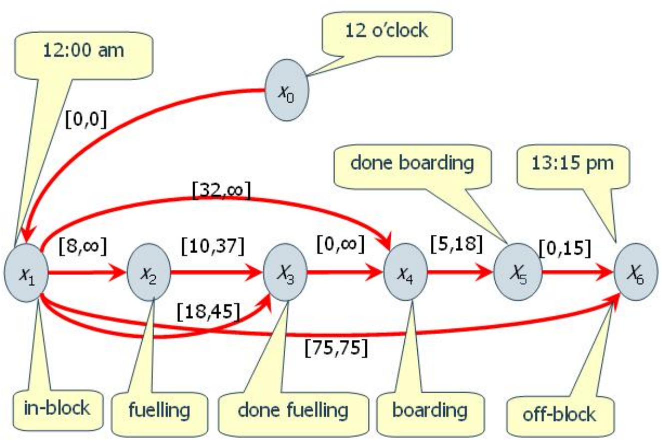

Fig. 2. A Simple Temporal Network of Flight KL310.

In this figure, variable x_0 is the temporal reference point: 12 o'clock. Variable x_1 corresponds to the moment the aircraft goes in-block, whereas x_2 corresponds to the fuelling activity. The temporal constraint [8,∞] between x_1 and x_2 denotes that fuelling can start 8 minutes after in-block at the earliest, and that there is no direct upper bound known. Fuelling itself can last anywhere between 10 and 37 minutes. Thus, the transition between 'fuelling' x_2 and 'done fuelling' x_3 is constrained by [10,37]. The same can be done for all other constraints. If no temporal constraint is known, this is denoted by [0,∞].

Of course, a larger STN can be created to encompass both flights. As a next step, we will demonstrate how such a STN can be decoupled. Figure 3 below shows this STN, in which flight Y is added to flight X. The figure illustrates how the STN can be decoupled in two parts: the first (shaded) matching the network of the fuelling company, the second (spotted) that of the boarding company.

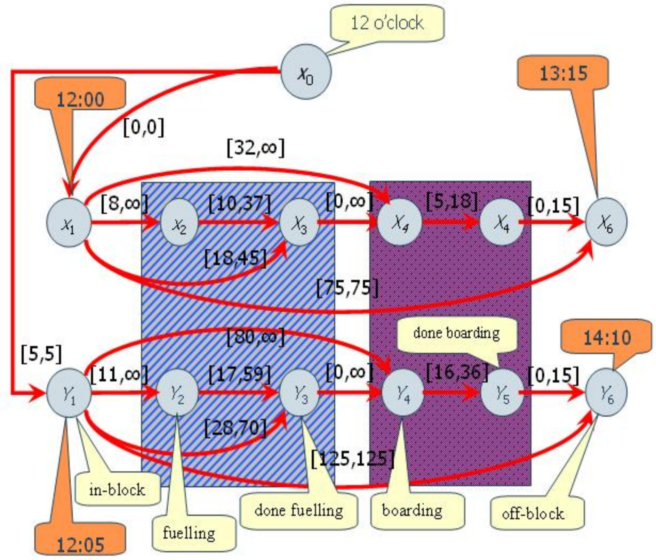

Fig. 3. An STN of aircraft X en Y and a possible decoupling.

When decoupling the boarding from the fuelling company, extra constraints should be added to ensure that no dependencies exist between different service providers. Below, the two STNs resulting from the decoupling are given (Figures 4 and 5) including these extra constraints.

In Figure 4, the in-block variables x_1 and y_1 have been excluded since they do not form part of activity fuelling itself. Instead, temporal constraints are placed between x_0 and x_2 / y_2. For example, the set of constraints [5,5] and [11, ∞] between variables x_0, y_1 and y_2 is translated into the constraint [16, ∞] between x_0 and y_2 to reflect that fuelling of aircraft Y should start at least 5 + 11 = 16 minutes after 12:00 noon. Similarly, the set of constraints [5,5] and [28,70] of Figure 4 is translated into the constraint [33,75]. Apart from that, no extra constraints have been added as a result of the decoupling. Only a local constraint (indicated by the dashed arrow) has been added to capture that there should be at least a 10-minute gap between fuelling flight 1 (X) and flight 2 (Y) to allow the fuelling vehicle and its personnel to get from stand A17 to A23. This local constraint has been added after decoupling by the fuelling company itself.

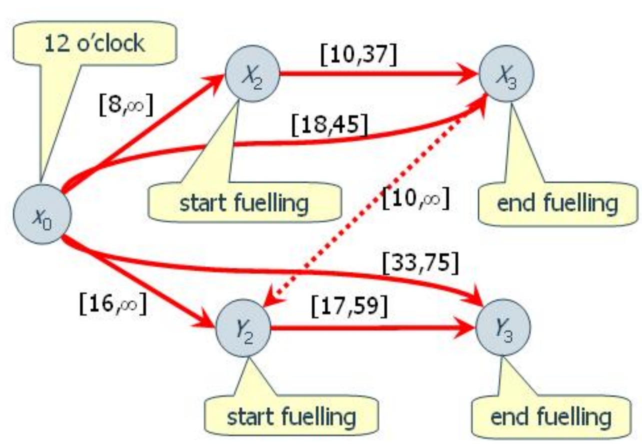

Figure 4: The decoupled of the fuelling service.

In Figure 5, the boarding service is decoupled from the overall STN. In this figure, an extra constraint is created to decouple boarding from the previous activity: fuelling. This constraint is the temporal constraint $[45,\infty]$ between x_0 and x_4. It is obtained through the following process. First, constraint $[32,\infty]$ between x_0 and x_4 is copied from the original domain to the boarding domain (we can replace x_1 with x_0 because of the constraint [0,0] between them).

Other extra constraints for flight 1 follow from constraint [0,15] between x_4 and x_6. Since the aircraft should go off-block at 13:15 p.m. and boarded passengers shouldn't wait longer than 15 minutes, boarding should end at least 60 minutes and at most 75 minutes after in-block. For flight Y, similar extra constraints are added.

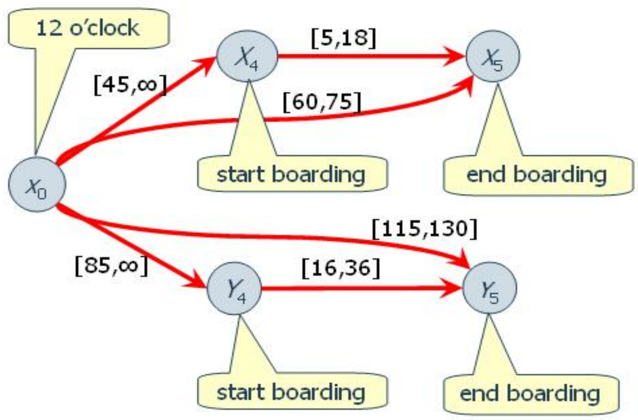

Fig. 5. The decoupled boarding service

Having created an STN of the planning problem, and having decoupled this STN into local STNs, we now proceed to solve the decoupled STNs. A solution to an STN is an assignment $x_i = \tau_i$ of values to the time point variables $x_i \in X$ such that all constraints $c_{ij} \in C$ are satisfied. For STNs, a variety of efficient solution techniques exist (see e.g.[11] [12]) We will show what type of solutions may be reached when applying these algorithms to our running example.

For Figure 4, it is not difficult to find a solution. Since for aircraft X fuelling can start at t=8, whilst aircraft Y should wait until t=16, it seems natural to first fuel X, then Y. If we further assume that the fuelling company wants to minimize the time required for fuelling (10 minutes for X, 17 for Y), we obtain the solution depicted in Figure 6.

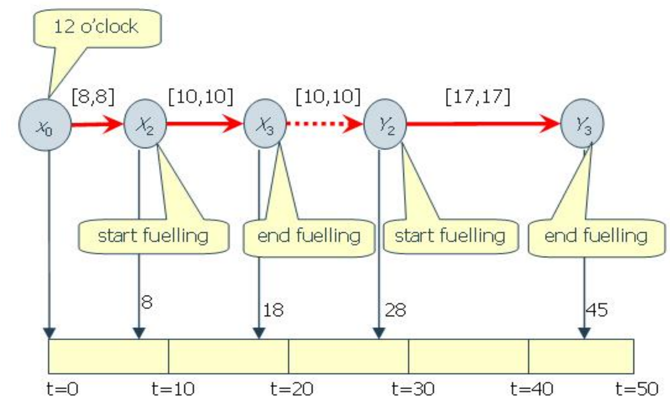

Fig. 6. An example solution for the boarding company.

In this figure, the dashed arrow between x_3 and y_2 indicates a local constraint: the minimum time between the end of fuelling aircraft X and the start of fuelling aircraft Y. This constraint may depend on a variety of factors: the distance between both aircraft, the personnel and fuelling vehicles disposable for both services[3], etc.

Figure 6 gives an example solution to one of the local STNs that results from applying decoupling to the running example. Using the algorithms described in [1], we can try to solve all local STNs. As a last step, it suffices to merge these locally solved STNs to get an overall STN. Due to the Mergeable Solutions Property of Hunsberger's decoupling algorithm, this STN – the pre-tactical stand and services plan – is guaranteed to be conflict-free.

IV. PROTOTYPE RESULTS

Based on the turnaround model and decoupling methodology described in the previous section, a prototype has been developed. This prototype was intended to demonstrated the feasibility of the concept. In figure 7, a general overview of the prototype and its input and output streams is presented.

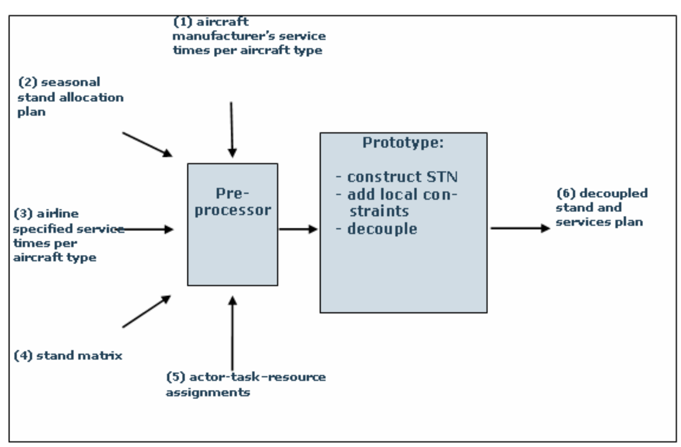

Figure 7: Design of the Prototype

[3] In this example, it is assumed that the same vehicle and personnel will service aircraft X and Y in consecutive order. Moreover, X is located near Y, since gate A23 is at the same pier as gate A17 (see the original example description).

In Figure 7, the following steps have been implemented:

1. Read (1) the aircraft manufacturer's minimum service times, (2) the list of aircraft to be serviced in the stand allocation plan, (3) the airline's service norm times, (4) stand matrix defining travel times between stands, and (5) the actor-task-resource assignments specifying the tasks each actor is responsible for (e.g. boarding and de-boarding for the boarding company), and the maximum number of resources available. After reading these input files, the data extracted is stored in adequate data structures (pre-processing).
2. Construct a large Simple Temporal Network (STN) based on the stored data structures of inputs (1), (2) and (3).
3. Add local constraints based on the (5) task-actor-resources assignment to the complete STN.
4. Use decoupling to split up the complete STN into local STNs for each service provider. Next, all local constraints are removed to allow a maximum of flexibility for each service provider.
5. Output the stand and services plan, listing for each service of each service provider a plan matching the original stand plan, to the output directory specified by the user.

The prototype (implemented in C++) has been tested using a realistic scenario. To this end, on August 2 2007 at 2:15 p.m. a total of 37 KLM flights have been recorded at Amsterdam Airport Schiphol. The performance of the prototype can be divided into two steps that the prototype needs to perform:

- The construction of a minimum Simple Temporal Network based on all input data
- The decoupling of the STN into local networks

In fact, both tasks were completed by the prototype within 1 second for the given scenario of 37 flights. Although the scenario is not large, this is very quick, taking into account that the temporal network that is constructed includes over 800 nodes and thousands of temporal constraints.

Figure 8 below gives an example output produces by (a postprocessor of) the prototype: a graphical representation of all flights planned in their timeslots.

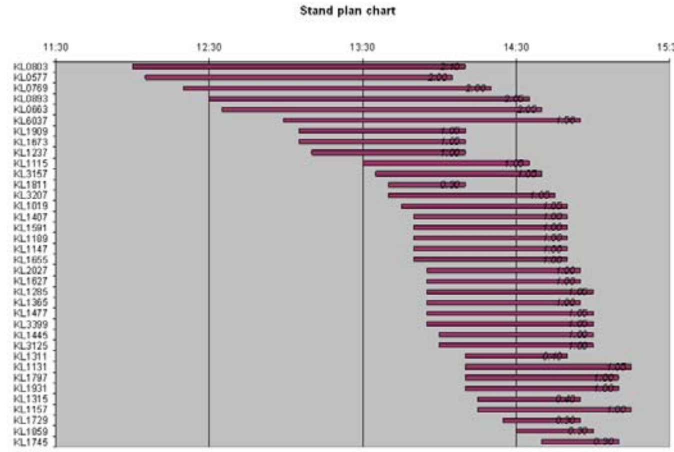

Fig. 8. Stand and services plan produced by the Prototype (Global View)

What remains to be shown now is the tactical advantages the decoupling approach could bring. This has not been tested yet, but the idea behind it can be demonstrated by means of a simple example. After running the prototype in the pre-tactical planning phase, a set of decoupled plan representations is created which can be utilized by the service providers to do their own planning. For instance, a fuelling company may receive two maximum intervals for aircraft X and Y to be fuelled; within this interval, as we have seen, the prototype also provides a minimum interval based on the minimum time required to fuel these specific aircraft. Having no knowledge about any fuelling company specific constraints, the prototype typically chooses the earliest start time for both these minimum intervals:

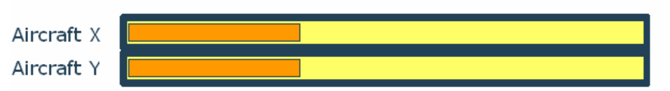

Fig. 9. Example local plan for fuelling aircraft X and Y

Based on this prototype output, however, the fuelling company is free to pre-tactically plan its services as it sees fit. As long as fuelling stays within the yellow bar, the local solution is guaranteed to be conflict-free with respect to all other ground handling services around X and Y. For instance, when the fuelling company only wants to employ one fuelling vehicle for aircraft X and Y, it may choose to locally plan these services as follows:

Fig. 10. Example pre-tactical plan for fuelling X and Y

In Figure 10, the fuelling company has added a local constraint specifying that aircraft X should be fuelled before Aircraft Y. Within this order, there is still some margin (compare the orange bar with the encompassing yellow bar) for both aircraft to slightly shift the fuelling service if required. More importantly, both aircraft can now be fuelled by the same fuelling vehicle without conflicting with one another, with other aircraft to be fuelled, and with all other ground handling activities at the airport.

Now let us assume that on the day of operations aircraft X arrives 5 minutes late. This means that the start and end time for fuelling X needs to be delayed by 5 minutes. Since the yellow rectangle is still larger than the orange one, however, it is possible to simply adjust the scheduled time for fuelling Aircraft X by “right-shifting” the orange block 5 minutes:

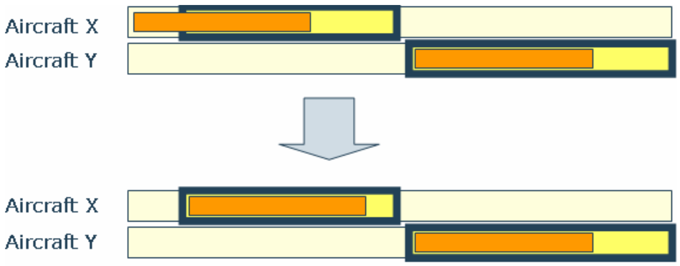

Fig. 11. Tactical shifting based on a 5 minute delay of X

The result is shown in the bottom part of Figure 11. Aircraft X will be fuelled a little later than scheduled originally, without interfering with Aircraft Y. It was not necessary to adjust the planning for Aircraft Y.

Let us assume however that the delay of X, originally estimated to be 5 minutes, grows to a delay of 30 minutes. In that case, it may not be possible to simply shift aircraft X within its local planning margin – the delay is too large to fit within the yellow bar. Something else needs to be done here. Since we know that the local constraint of fuelling X before Y was added after decoupling and by the fuelling company itself, however, it is not difficult to find a solution.

In the original prototype output, both aircraft X and Y could be fuelled somewhere in the entire range of the maximum interval. Therefore, the fuelling company can simply change its locally added constraint, fuelling aircraft Y before aircraft X instead of the other way around. This solution is shown in Figure 12:

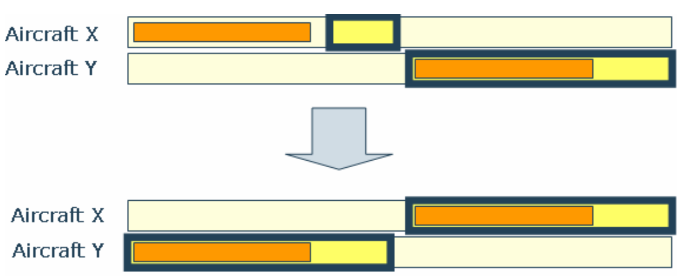

Fig. 12. Tactical shifting based on a 30 minute delay of X

In this case, re-planning has been performed on a local level. Because of the decoupled plan representation, produced by the prototype, a solution could be found locally – again without involving any other aircraft or service providers.

V. Discussion

In this paper we have presented the first results of a new approach for planning: extreme decoupling. This new approach has been applied to the domain of ground handling, demonstrating that in this domain pre-tactical planning based on decoupling actually works. Next, by use of a number of illustrative examples, we have shown that the approach can offer important tactical advantages. These advantages will show up when disruptions necessitate re-planning of the original plan. In these cases, the decoupled local plans offered by the proposed new planning approach ensure that re-planning can be kept as local as possible – whilst guaranteeing that a solution does not conflict with other plans. This enables ground handlers to solve many tactical disruptions locally, thus drastically reducing the co-ordination overhead involved in negotiating with other parties. Given the large number of plan disruptions occurring daily at airports, and the increase expected in air traffic, such a planning tool seems to be a valuable asset.

VI. Future Research

In the future, a number of new steps are foreseen. First of all, the prototype developed in Year I shall be extended towards a full-blown planning tool, assisting the user by means of a graphical user interface into the pre-tactical planning of a large variety of ground handling services. Second, the planning tool shall be tested against a much larger scenario; further, testing of its tactical advantages should be performed in a realistic setting involving real planners to quantify the tactical benefits of the approach. Third, software support can be offered to the user when re-planning its plan based on the decoupled output of the initial prototype.

Apart from this, some entirely new features are foreseen to be added to the existing model and prototype. First, an extension of the model is foreseen involving the allocation of resources. To this end, the travel times of resources between stands, the number and availability of vehicles or personnel and other constraints will be added to the model and planning tool. This will allow local planners to use their own task assignment system to determine at any point in time which task should be executed when, and by which resource.

Additionally, some of the ideas presented in brief in chapter 7 of this document can be further developed to enhance the *flexibility* of the decoupling approach. For instance, future research could focus on the level of decoupling. The domain may be partitioned not into separate ground handlers, as is done now, but to a next level: into individual equipment (fuelling vehicles, catering vehicles, etc.) or personnel. Alternatively, one may group certain service providers together (e.g., cleaning and catering) for reasons of efficiency. Yet another topic concerns the implementation of a mechanism to upscale the level of decoupling when local re-planning is not feasible. In such a mechanism, a new decoupling is produced to group two (or more) service providers together if either one of them cannot find a re-planning solution individually.

VII. Publications in the Project

The first year of research has resulted in a research paper presented at the IMCSIT-conference in Poland in October 2007 [6].

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INO CARE III "Towards Fault-Tolerant Cooperative Air Traffic Management" First Year Project Report

Jean-Pierre Briot, Zahia Guessoum, Olivier Marin, Minh Nguyen-Duc, and Jean-François Perrot

***Abstract*—This report summarizes the work performed at LIP6 on the INO CARE III project "Towards Fault-Tolerant Cooperative Air Traffic Management" during the year 2007.**

***Index Terms*—Air Traffic Management, Fault-Tolerance, Multi-Agent Systems, Replication**

I. Motivation

Because of its very large scale, complexity, and dynamicity, we believe that the future of air traffic management lies in hybrid distributed cooperative control systems, including human experts (air traffic controllers) and also intelligent computer support through artificial agents. As a distributed application, air traffic management control includes possibility of partial failures, as this is a fundamental characteristic of distributed applications.

The fault tolerance research community has developped solutions (algorithms and architectures). For air traffic control, the focus of activity and criticality may depend on many dynamic properties, related to the air traffic domain (e.g., locations of planes, flight plans, congestion in airports, dependences between controllers, etc.), as well as to the computational domain (dependences between assistant agents, relative importances of information servers, roles of agents, etc.).

In consequence, our long-term approach is to enable the multi-agent system itself to dynamically identify the most critical agents and to decide which fiabilisation strategies should be applied to them (e.g. based on the concept of replication). Air traffic control is a domain where such a technology would find an application. This is the reason why this project was born.

However, we know that finding a real application is no easy matter. Therefore, our short-term (first-year) objective was to select some scenarios with Eurocontrol in the field of air traffic control to better evaluate and assess our approach.

II. Methodology Followed during the First Year

A. Short-term

Through project meetings and contacts with Eurocontrol we tried to elicit guidelines for the construction of an eDEP-based demo to establish a common ground of understanding, as a basis for future and more elaborate studies.

Our starting point was our representation of the ATC system based on the previous work of Minh Nguyen-Duc at Eurocontrol (Nguyen-Duc [17]). Our main tool was the simulation platform eDEP [5][6], for which we obtained a license from Eurocontrol. Due to the Java-based modular structure of eDEP, it is possible to "plug-in" additional mechanisms such as software agents (also written in Java, using the DimaX platform). The heart of the matter is that these agents then execute in the context of an eDEP-based simulation, thus demonstrating their possible usefulness.

The first demo that we produced was shown at the kick-off meeting of the project, on May 7th, 2007, and referenced a a video on the project's web page. It was based on the *assistant agent* concept and purported to exhibit a *hand-over* procedure.

Two CWPs (*Controller Working Positions*) representing two adjacent sectors appear in the simulation. Each of the two CWPs is equipped with a DimaX "assistant" agent which monitors the simulated air traffic. In particular the two assistant agents detect aircraft that cross the boundary between the two sectors, and will start an hand-over. The detection is materialized by the appearance of a window carrying the collected information. Our goal was to prove the technical feasability of plugging in agents that would operate inside an eDEP simulation.

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However this set-up did not meet Eurocontrol's expectations, which are concerned with the future ATC system needed to cope with the forecast growth in air traffic. In particular, the future system shall integrate a number of safety and decision-support software tools (see the *First ATC Support Tools Implementation* (FASTI) program Petricel and Costelloe 2007 [18]). This will increase the human controllers' capacity (by flagging up problems and possibly suggesting solutions) at the expense of a complexification of their task. Our first proposal did not take account of that important aspect, and we were asked to concentrate on it.

We then had meetings in May, June and July with Eurocontrol representatives at Brétigny, Brussels and in Paris who gave us a most valuable advice and documentation. On this basis we produced a second demo which was shown at our second project meeting on September 4th. The principle of this demo was accepted. Its technical contents are presented herafter in the *Results* section.

B. *Long-term*

Most of the deliverables of the project are concerned with contributions of a fundamental nature, independent of a possible application scenario (deliverables #3 to #8). Accordingly, research work went on in the normal way at LIP6, with students working and publishing on their doctoral theses (see the *Results* and *Own references* sections).

Two doctoral students were mainly concerned by the project, namely Nora Faci and Alessandro de Luna Almeida. Nora's dissertation is to be defended on December 6, under the title *Un Mécanisme de Réplication Adaptatif pour la Conception et le Contrôle de SMAs Large-échelle Tolérants aux Fautes (An Adaptative Replication Mechanism for the Design and Control of Falut-Tolerant Large-Scale Multi-Agent Systems)*. Alessandro's defense is planned for the first term of 2008.

III. Results of the First Year

A. *Short-term*

N.B. This section is based on a paper currently submitted for publication :

A multi-agent approach to reliable Air Traffic Control, by Minh Nguyen-Duc, Zahia Guessoum, Jean-François Perrot, Jean-Pierre Briot [O4].

Our main result is to demonstrate how a MAS (*Multi-Agent System*) can be integrated in ATC software in a meaningful way. This forms the basis of future experiments concerning fault-tolerance issues of the MAS. For the time being, our contribution to fault-tolerance of the global ATC system resides in the role that our agents can play in helping human controllers manage their armada of support tools. Our idea is that the safety and power that the tools are expected to provide will only become effective if the controllers are able to make the most of the functionalities of their tools. We argue that the best way to prove a support system's reliability is to show that the ATC system, as a whole, can still provide full traffic control services when errors suddenly appear, by adopting a *Degraded Mode of Operation* (in the terms of the *Guidance Material for Contingency Planning* (ESP 2007 [6]).

1. Distributed ATC system :

The airspace is divided into many sectors the size of which depends on the average traffic volume and on the geometry of air routes. These sectors are grouped into regions each of which is under control of a single control center. For example, the Athis-Mons center is responsible for the air traffic in the Parisian region. There are usually two air traffic controllers to handle the traffic in each air sector: an *executive* controller who communicates with pilots, and a *planning* controller who plans his colleague's work.

To be precise, we consider that different control centers are all connected with a common flight data-processing center through the inter-center network (a WAN). On the other hand, in each control center one (or several) application server(s) host(s) the various software tools in use. These application servers are connected with the *Controller Working Positions* (CWP) by means of a local network (LAN). The LANs of the various control centers are connected via the inter-center WAN.

This architecture is summarized in Figure 1 below :

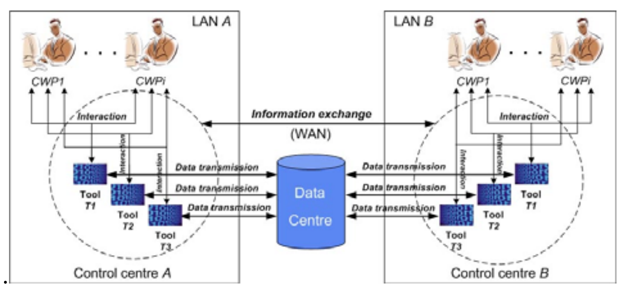

Figure 1. Basic future ATC system architecture.

A typical example of support tool is the *Medium-Term Conflict Detection* (MTCD) (see Petricel and Costelloe [18]). Once aircraft trajectories have been predicted, they can be used to detect medium-term conflicts. There also exist many other tools such as *Short-Term Conflict Alert* (STCA), *MONitoring Aid* (MONA), *Airspace Penetration Warning* (APW), and *Minimum Safe Altitude Warning* (MSAW).

Our aim is to provide each controller with a bird's eye view of this complex environment. In this setting information will be displayed about the state of the various tools as well as warnings if necessity arises. The obstacles created by distribution over several computers are taken care of by managing communication over the network. For such a purpose a MAS is a natural choice. Here is a sketch of a typical situation we wish to handle.

2. Outline of an example scenario

We consider two (executive) controllers (called Co_1 and Co_2) who are responsible for two neighboring sectors (called S_{10} and S_{12}), separated by the border between two control centers (called *A* and *B*). They are often in handover situations, *i.e.* they have to transfer the control of aircraft flying from one sector to the other (and therefore from the resonsibility of one control center to the other center). One of their main concerns for controllers is to deal with conflict situations where e.g. the trajectories of two aircraft are getting dangerously close.

Suppose that at a given moment there are several potential conflicts among which a particular one concerns two aircraft: *TH003* flying from sector S_{10} to sector S_{12}, and *TH004* flying in the opposite direction. Suppose also that conflicts are going to happen in S_{10}. We try to assess the possible behavior of controller Co_1 who is responsible for this sector.

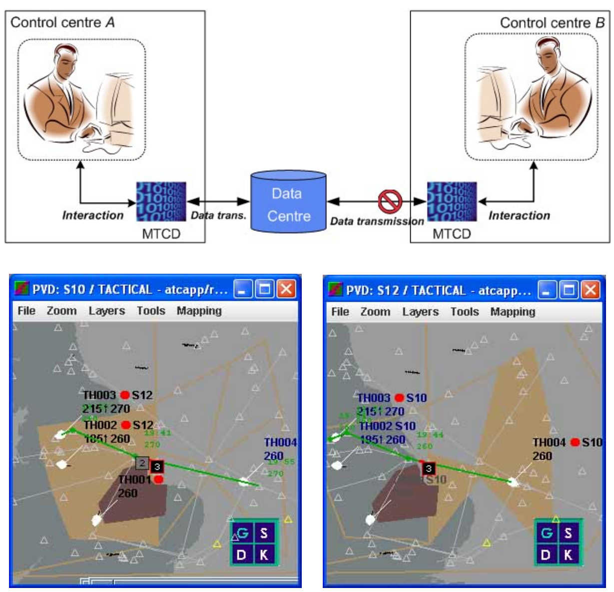

Figure 2. Typical example: *TH001*, *TH002* and *TH003* fly from S_{10} to S_{12}; *TH004* flies from S_{12} to S_{10}; *TH001* is potentially in crossing conflict with *TH002* and *TH003*; *TH003* and *TH004* are potentially in opposite conflict.

Conflict prevision on Co_1's sector is normally performed by his copy of MTCD. On each detected conflict, he has to choose between solving it (by asking some trajectory change from one of the pilots) or postponing its solution. For this purpose, S_{10} manages an ordered list of detected conflicts. Therefore, he needs to decide to (or not to) resolve a conflict at least *T* minutes before it happens. Indeed, *T* is common to all the detected conflicts, and it has to be sufficiently large so that the controller can perform good conflict sequencing.

Suppose now that a network failure occurs. More precisely, center *B* is disconnected from the flight data-processing center (see the basic ATC system architected illustrated by Figure 1). Consequently, a demand for exit flight level change for *TH004* sent by Co_2 to the data-processing center is lost. At the same time, the flight data of *TH004* are no longer accessible from center *A* and therefore unusable for Co_1's MTCD.

This failure prevents Co_1's MTCD from detecting potential conflicts not only for *TH004*, but also for all the aircraft flying from center *B*. However, it still correctly detects the "local conflicts" that only concern the aircraft flying in Co_1. So we can see it as "locally available".

Consider now controller Co_1's reaction to the unavailability of his MTCD: in order to continue managing as efficiently as possible his list of detected conflicts, he clearly needs to be informed of

a) the global unavailability of his tool, which means that he now has to detect himself all potential conflicts.

b) its "local availability", which conversely implies that he can still trust his MTCD for aircraft that are currently in his sector.

We conclude that the information that should be delivered to controllers in case of some dysfunction may be of an elaborate nature. We are trying to provide this sort of messages through a *Multi-Agent System*. We describe this system in two steps: first the individual agents, then their organization.

3. Agents

Since our agents have to take care of the monitoring of software tools and of the communication with the controllers, we use different kinds of agents collaborating to perform these two common tasks. We currently use two monitoring agents for each tool, *i.e.* a data sentinel and a computation sentinel, and as well as an assistant agent for each controller. Their respective roles may be described as follows:

1. *Data sentinel agent*: observes the input and output data of a specific software tool and communicates with other agents in order to discover data losses;
2. *Computation sentinel agent*: observes the input and output data of a specific software tool and communicates with other agents in order to discover computation faults;
3. *Assistant agent*: communicates with other agents in order to determine the automated tools' availability, and informs a controller of this availability; an assistant agent can observe the controller's actions in such a way that it can notify the monitoring agents of relevant events.

Note that these agents need not to be very complicated. A monitoring agent simply reacts to technical incidents that it discovers itself or of which it is notified by other monitoring agents. An assistant agent is endowed with some limited reasoning capacity allowing it to propose predefined corrective actions to be performed on well-known incidents. The simplicity of the agents brings to the MAS not only more reactivity, but also more robustness. Any agent can be implemented as a single-threaded object in order to ensure its reliability as discussed below.

4. MAS organization

On each LAN in a control center we install a group of coordinated agents that are distributed over the whole local network. Each local group of agents is composed of assistant agents and of monitoring agents. We associate with each *Controller Working Position* (CWP) an assistant agent. Each tool instance is observed by monitoring agents. It should be noticed that monitoring and assistant agents may be hosted on any of the machines, or even on additional independent network nodes, as long as they retain the capacity to display information on the controller's client machine.

When an incident occurs, the related tool's monitoring agent first discovers the critical situation by using the data it gathers from the tool's input/output, as well as the information it receives from other monitoring or assistant agents. It then transmits information about the tool's state to the assistant agents of the CWPs that use this tool. These assistants display green/yellow/red flags on their controller's screen, thereby indicating the tool's total/partial availability, together with the relevant information.

By exchanging observed tools' data and controllers' actions with each other, the agents are able to notify the controllers of what actions they should consider taking after the perturbation caused by the incident. For instance, in the scenario presented above and explicited below, the monitoring agents exchange events of request for data change so that they can find out lost data due to network failures. Then when the controllers see this information shown by their assistants, they know that the related aircraft's flight plan is inconsistent and that they cannot use MTCD to detect conflicts for it anymore.

5. *eDEP-based simulation*

To our knowledge, the future ATC system envisioned by Eurocontrol is not yet implemented. Moreover, any novel application to a critical system like ATC has to be extensively tested in simulations before its real world implementation. Therefore, we built our MAS into a simulation environment, thus turning it into an Agent-Based Simulation (ABS). For this purpose we used the eDEP platform (Early Demonstration & Evaluation Platform) in its latest version eDEP 2007 [6], which offers not only realistic air traffic data but also a distributed simulated ATC environment. Since eDEP is implemented in Java, we programmed our MAS with the Java-based DimaX platform (*Développement et Implémentation de SMA au-dessus de DarX*) (DimaX 2007 [4]).

eDEP uses RMI (*Remote Method Invocation*) to distribute its components over a LAN. It provides a set of standard ATC entities, *e.g.* "airspace" (a database of static airspace information); "integrated air surveillance" (a database of surveillance radar tracks); "initial flight plan" (an initial plan that defines route constraint points and altitude limits); "trajectory predictor" (a trajectory prediction algorithm which uses aircrafts' kinematic models to predict the real motion of a particular aircraft); and *Controller Working Position* (the principle graphical interface to the system based on a plan view display of the control sector).

The support tools for air traffic controllers, *e.g.* STCA and MTCD, are implemented in eDEP as independent components which can run on different machines.

DimaX gives a generic and modular agent architecture, and allows high heterogeneity in agent types (reactive, deliberative and hybrid). It is based on the extension of modeling and implementation facilities offered by object-oriented languages. In DimaX, an agent at the smallest granularity is simply a single-threaded object, and a complicated agent can be constituted by smaller agents. Also, this platform allows adding new behaviors to any agent by using integrated programming libraries.

Since we would like our MAS to be used in a critical socio-technical system like ATC, the MAS itself has to be reliable. DimaX can help with developing such MAS. This multi-agent platform is the result of the integration of its previous generation (named DIMA) with a fault-tolerance framework (namely DarX : Marin et al. 2003 [16]), which brings in services, *e.g. Fault Detection Service* and *Replication Service*, which automatically makes any MAS built from DimaX fault-tolerant.

In our current simulations, we manage at least two *Controller Working Positions* (implemented by the CWP component in eDEP), belonging to two different control centers. The LAN of each control center is realized on at least two computers (one for the CWP and the other for the application server). The data-processing center is realized as a separate third machine. This machine together with the two LANs make up our image of the inter-center WAN. On each application server runs a copy of each of five tools, *i.e.* MTCD, STCA, MONA, APW, MSAW (also as eDEP components).

The integration of our DimaX agents and eDEP components follows the FIPA 2001 *Agent Software Integration Specification* . The DimaX platform already has a generic wrapper agent ready to provide any other agent (*e.g.* a monitoring agent or an assistant agent) with services which allow this one to connect to the eDEP components it requires. Special wrappers are then built by extending the generic one.

Using the three agent types explained above (paragraph 3), as a first step we install two monitoring agents and two wrapper agents for each software tool:

1 *XXX_DataSentinel*, and *XXX_ComputationSentinel*: they observe the XXX[1] component's input/output data and communicate with other agents in order to discover faults;

2 *XXX_ObservationWrapper*, and *XXX_GeneralWrapper*: they are special wrappers which respectively provide XXX observation and general-purpose services to the two other XXX_agents;

[1] Tool name, *e.g.* MTCD or STCA.

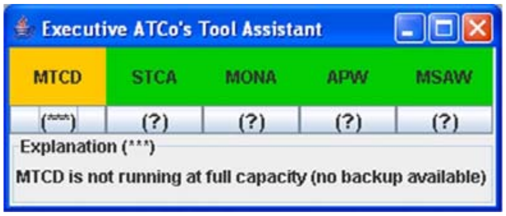

Figure 3. CWP_Assistant's user interface.

Additionally, we endow the CWP with a *CWP_Assistant* which communicates with other agents in order to determine the availability of the automated tools, and to show this availability in its user interface. Figure 3 illustrates the CWP_Assistant's user interface. It uses green/yellow/red flags to display the tools' status.

6. Simulation of the example scenario

The experiment runs on the following interconnected machines:

1. Two client machines hosting two CWPs for two controllers belonging to two different control centers (centers *A* and *B*).
2. Two tool servers hosting two MTCD instances for the two control centers.
3. One data server placed in the common flight data-processing center.

In this scenario, we only consider a disconnection of a controller center from the flight data-processing center.

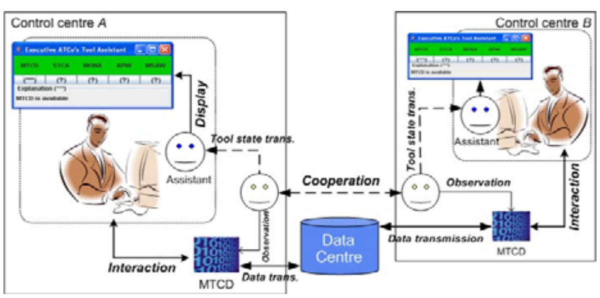

Figure 4. All machines run smoothly and are fully connected in a handover situation.

At first, all machines run smoothly and are fully connected in a handover situation (*e.g.* there are aircraft flying from the control center *B* to the control center *A*). Each controller has unlimited access to the tool server on his LAN and can freely obtain the flight data he needs. The assistant agents display green labels indicating that the software tools are working at full capacity.

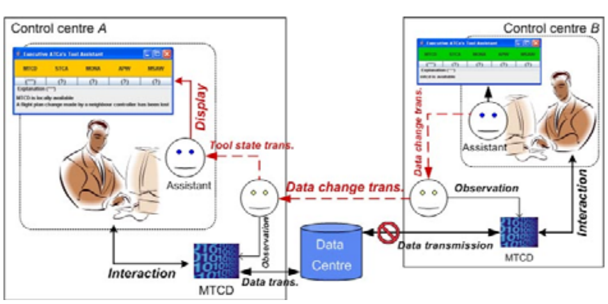

Figure 5. Control center *B* is disconnected from the flight data-processing center (1st phase).

The controller in center *B* (called *CB*) then makes a flight data change request (*e.g.* a demand for exit flight level change for an outgoing aircraft). However, due to some accident, control center *B* has been disconnected from the flight data-processing center. Due to the disconnection, this request is not sent to the data center.

Now, CB's assistant agent detects that a data change request was issued by *CB*. It notifies the data sentinel agent of MTCD in *B* of this request. This agent in its turn informs the monitoring and assistant agents in control center *A* through their simulated WAN connection.

The data sentinel agent of MTCD in *A* discovers that no such flight data change was received from the data-processing center. This also means that the flight data concerning an aircraft which is controlled by center *B* are no longer accessible from *A* and therefore are unusable for conflict detection.

In consequence, the assistant agent of the controller in center *A* displays a yellow flag, informing his controller that the software tool is only available locally, *i.e.* it only gives correct results for aircraft under control of center *A*.

Figure 6. Control center *B* is disconnected from the flight data-processing center (2nd phase).

Knowing this, the data sentinel agent of MTCD in control centre *A* signals back to the monitoring agents in *B* that there was on its side a flight data change request which was not taken into account. This agent notifies the *CB*'s assistant agent of this incident.

Finally, the *CB*'s assistant agent then displays a red flag, informing his controller that the software tool is now unavailable.

7. Related Work

In order to take into account human factors in critical socio-technical systems, published research either specifies users' working procedures or applies system design methods that help to prevent human errors. Little work has dealt with the daily relation between human operators and their powerful equipments, particularly in situations where technical incidents happen. On the other hand, fault-tolerant methods applied to this kind of system have mainly solved purely technical reliability problem.

Concerning the use of so-called "sentinels" in fault-tolerant component-based systems, as well as in certain MAS, the work of Klein, Dellarocas and colleagues [2, 14, 15] is also related to the monitoring of a complex critical system. However, they do not use simple communicating sentinel agents but complicated "sentinel components" to detect and deal with exceptions occurring inside application components. These "big" sentinels hence have their own reliability problem. Besides, Hägg [13] and Shao et al.[20, 21, 22] employ sentinel agents to detect and recover errors in negotiation processes between other BDI agents. Nevertheless, these application agents have to be "small" enough for the sentinel agents to be able to fully inspect their code. This condition does not hold in a system having complicated equipments like ATC.

B. *Long-term research*

Our main results this year deal with estimating agent criticality and with the allocation of resources (placing replicas on machines). Recall that the criticality of an agent is informally defined as follows, with respect to organization of agents to which it belongs: it is the measure of the potential impact of the failure of that individual agent on the behavior of the whole organization.

We are currently experimenting with several strategies in order to estimate the criticality of an agent. The issues are:

What kind of information will be pertinent ?

And how can we obtain it ? (statically or dynamically, in a way explicitly stated by the application designer, or inferred by external observation, e.g., amount of messages exchanged, or by internal observation, e.g., plans of an agent, etc.).

As a first strategy (Zahia Guessoum *et al.* 2005, 2006 [11, 12]), we used the concept of a *role*, because it captures the importance of an agent in an organization, and its dependences to other agents. A role, within an organization, represents a pattern of services, activities and relations. As such, it captures some information about relative importance of roles and their interdependences. The examination of further strategies was continued in 2007.

1. Strategy for estimating agent criticality based on dependencies

In this second strategy, we use the notion of dependence between agents as a clue for estimating criticality. Intuitively, the more an agent has other agents depending on it, the more it is critical in the organization. Interdependence graphs were introduced to describe the interdependence of agents. These graphs are defined by the designer before the execution of the multi-agent system. However, complex multi-agent systems are characterized by emergent structures which thus cannot be statically defined by the designer.

Our approach is to explicitly represent dependencies between agents as a weighted graph, and to provide a mechanism to automatically update its respective weights according to communications between respective agents. This graph can then be interpreted to define each agent's criticality (Nora Faci [O5]).

2. Strategy for estimating agent criticality based on plans

In this setting, agents are supposed to hold plans (represented as and-or graphs or as Petri nets) and to be willing to communicate them. An algorithm is proposed to compute the criticality of agents using the plans they provide. This algorithm has been tested and found (1) more efficient than a random strategy (2) almost as efficient as the optimal strategy (without any failure). (Alessandro de Luna Almeida *et al.* [O1]).

For a systematic comparison of strategies for the evaluation of criticalities, see Deliverable #5 *Comparative Study of the Various Decision/Information Strategies and Models for Controlling Replication-Based Fault Tolerant Multi-Agent Systems*. As regards the possible use of a strategy based on a multi-criteria approach or on a "ranking" technique, see Deliverable #8 *Multi-Criteria Decision Aggregation and Ranking Approaches for Combining Multiple Information Strategies to Decide Which Agents should be Replicated.*

The problem of optimal allocation of replicas over the network is a second step towards global reliability of the overall system.

3. Market-based mechanism for replica allocation

We introduce a QoS-based economic model (QoS for *Quality of Service*) because the economic approaches have provided a fair basis in successfully managing resources that are decentralized and heterogeneous. The proposed economic model aims to provide QoS guarantees at the application level. It is based on a replication-service negociation between the resource providers and the consumers. This negotiation attempts to improve the quality of the replication service (e.g., optimize the number of failures and the performance of the system). (Nora Faci [O5] Zahia Guessoum *et al.* [O6])

4. Heuristics for optimization of replica allocation based on an evaluation of available resources

The DarX middleware provides a failure rate for each machine on the network. From it a probability of agent failure is computed, as a function of the machines on which the agent is replicated. The resource allocation problem is formulated in a way that permits a near-optimal allocation of replication resources based on the criticality of the agents and on their failure probability. Near-optimality means that critical agents have a low failure probability.(Alessandro de Luna Almeida *et al.* [O2] [O3]).

IV. Discussion

In section III we describe the way in which a MAS can help in mitigating the effects of software malfunction in a complex critical system like ATC and building confidence for its users, *i.e.* air traffic controllers. Because of safety restrictions, experiments on real traffic control are not allowed. Therefore, we have developed an Agent-Based Simulation by using the ATC simulation platform eDEP, and the multi-agent platform DimaX. The software agent integration has followed the FIPA

2001 specifications.

This simulation has been used to demonstrate the usefulness of our MAS for the future ATC system to air traffic controllers. Indeed, we run a typical applicative scenario that shows the reaction of our MAS to the instant unavailability of a software tool due to a network failure. The next step will be to perform human-in-the-loop experiments with controllers in order to validate the conformity of the information provided to them with what they require in situations where some software tools are not available.

However, the agents themselves, like any supplementary layer added to a system, bring their own liability to fault. A natural extension of the present work will be to set up mechanism for ensuring a degree of fault-tolerance at the agent level, which would be of a computational, domain independent nature. The possible techniques would include adaptive replication and exception handling (Marin et al. 2003 [16], see also Deliverable #7).

Of course, the complete realization of the project would be obtained with an experimental system where the replication technique described in the long-term subsection III.B would be used to ensure fault-tolerance in an extended version of the simulation described in subsection III.A.

V. Open Issues Selected for Next Year

In order to experiment with the application to our scenario of the replication-based techniques, we need precise information about the intended implementation of the future ATC system.

This would address both the architecture of data exchange and the installation of support tools. Notably, it essential to have more details on the way software tools are distributed over the local network of each control center (how many application servers ?) as well as details on the communication pattern between them. It would also be important to know which reliability techniques are planned to be used.

VI. Own Publications on the Project

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Safety Modelling and Analysis of Organizational Processes in Air Traffic

Sybert H. Stroeve, Alexei Sharpanskykh, Henk A.P. Blom

Abstract— **This paper presents the results of the first year research in the EUROCONTROL CARE Innovative Research III project on safety modelling and analysis of organizational processes in air traffic. It is the objective of this research project to enhance safety analysis of organizational processes in air traffic by development of formal approaches for modelling, simulation and analysis of organizational relationships and processes. These approaches should explicitly relate organizational processes at the blunt end (e.g. management, regulation) with working processes at the sharp end where accidents may occur. The year-1 research includes a literature survey, leading to identification of promising approaches, and application of the most viable approach to an air traffic case on safety occurrence reporting. The applied approach describes a formal organization in three views: (1) organization-oriented view, describing roles, their interactions and authority relations, (2) performance-oriented view, describing goals and performance indicators, and (3) process-oriented view, describing tasks, processes, resources and their relations. A fourth agent-oriented view represents the link between the role-based formal organizational model and the agents that fulfil the roles. The performance of the agents is determined by the formal organization, but also influenced by the stochastic dynamics of interacting agents. With these four interrelated views a broad scope of organizational modelling can be achieved. The modelling approach supports safety assessment by identification of inconsistencies and evaluation of safety-relevant performance both at the level of the formal organization and at the level of interacting agents.**

Index Terms—**Safety, Organization, Air Traffic, Modelling**

I. Introduction

In complex and distributed organizations like the air traffic industry, safe operations are the result of interactions between many entities of various types at multiple locations. Such organizations can be described at various aggregation levels. At a high aggregation level, such a description discerns companies/corporations (e.g. air traffic control centres, airlines, airports, regulators), zooming in at lower aggregation levels it discerns departments/groups (e.g. safety department, control tower group, operational management team), and at the lowest aggregation level it distinguishes the performance of single human operators executing organizational tasks in their organizational habitats, usually including knowledge and procedure intensive interactions with technical systems and other human operators (e.g. pilots, air traffic controllers, maintenance personnel, supervisors). In safety-focused organizations like airlines and air traffic control centres, it is crucial to have a good understanding of the organizational structures and dynamics at the different aggregation levels, since misconceptions and inconsistencies in the organizational structure and dynamics may contribute to the development of incidents and accidents.

The importance of proper organizational processes for the safety of complex operations is currently well realised. It is generally acknowledged that the level of safety achieved in an organization depends on the constraints and resources set by people working at the blunt end (e.g. managers, regulators), which determine the working conditions of practitioners who are directly controlling hazardous processes at the sharp end (e.g. pilots, controllers, physicians). The well known Swiss cheese model of Reason [1] illustrates that accidents may occur if multiple holes, reflecting active failures and latent conditions in an organization, are aligned. Early ideas about the evolution of accidents in complex sociotechnical systems have also been put forward by Turner [2] and Perrow [3].

In the literature and in the risk assessment practice, the recognition of the importance of organizational processes for safe operations has mostly been accommodated by high-level conceptual models and to some extent by organizational influencing factors in accident models. Predominantly, formal risk assessment approaches focus on fault/event tree type of analysis, which uses sequential cause-effect reasoning for accident causation. Recent views on accident causation indicate that these types of accident models may not be adequate to represent the complexity of modern socio-technical systems [4]-[10]. Limitations of frequently applied accident models as fault/event trees include the difficulty to represent the large number of dynamic, non-linear interdependencies between organizational entities and their restrictive error-view on human performance.

To adequately account for the effects of the complexity of socio-technical organizations in safety assessment, above views indicate that we need analysis approaches that account for the variability in the performance of interacting

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organizational entities and the emergence of safety occurrences from this variability. In the terminology of Hollnagel [4] this is a systemic accident model. The systemic view considers accidents as emergent phenomena from the variability of an organization and thus passes the limitations of sequential accident models in accounting for the dynamic and non-linear nature of the interactions that lead to accidents. In current risk assessment practices, formal models that describe the variability of organizational processes and its effect on safety-relevant scenarios are largely lacking.

As a way forward for description of organizational structures and processes and inclusion thereof in air traffic safety assessment methods, NLR and Vrije Universiteit Amsterdam collaborate in an EUROCONTROL CARE Innovative Research III project. It is the objective of this research project to enhance safety analysis of organizational processes in air traffic by development of formal approaches for modelling, simulation and analysis of organizational relationships and processes. These models should describe the organization at different aggregation levels and should lead to emergent safety issues as result of performance variability and interactions of organizational entities. In other words, it is intended to develop an approach for systemic accident modelling of air traffic organizational processes.

The first year of this research project consists of (1) a literature survey on safety modelling and analysis of organizational processes, and (2) a first application of identified methods to a safety-relevant organizational process in air traffic. This paper describes both aspects of the first year. Section 2 provides an overview of approaches identified in the literature and our view how these can be used for systemic accident modelling of organizational structures and processes. Section 3 introduces an air traffic case for safety occurrence reporting and describes the development of an organizational model for this case. Section 4 presents the kinds of results that are obtained by the organizational modelling approach. Section 5 provides a discussion. Section 6 presents ideas for future research.

II. Literature Survey on Modelling of Organizational Safety

As a basis for the research on safety modelling and analysis of organizational processes, a wide-scope literature survey has been done [11]. This survey considers a variety of sources and viewpoints, which are presented in the following list.

- *Accident models*, describing views and models for accident causation in an organizational context. These models include sequential, epidemiological and systemic accident models.
- *Human performance and human error*, describing human performance in an operational context and the effect of its variability on the evolution of safety-relevant events. There exists a large volume of research on human factors and its relation to safe operations. Historically, there has been a considerable emphasis on human error and its analysis in sequential and epidemiological accident models. In systemic accident modelling the focus is not on human error as such, rather the effects of variability in human performance are analysed for the role of the human in the organization.
- *Organizational and safety culture*, describing culture in an organization and its effect on safety. These aspects can be seen as conceptional reflections on the variability in work processes, i.e. as moderators of the variability in the human performance. In other words, they reflect the impact on “the way we do things around here”, which is an informal, behaviour focused notion of organizational culture [12].
- *Multi-agent models*, describing models of agents and their interactions for the representation of emergent behaviour in complex multi-agent systems.
- *Organization theory*, describing views on structures and dynamics of human organizations using methods from a wide variety of disciplines as economics, psychology, sociology, political science, anthropology, and system theory; related practical disciplines include human resources and industrial and organizational psychology.
- *Enterprise architectures*, describing enterprise-wide, integrating modelling frameworks used to represent and manage business processes, information systems and personnel.

The first three aspects considered in above list belong to the core of safety science and are well known by researchers in ATM safety. The last three aspects are less well known and consider descriptions of formal structures and relations in organizations, as well as multi-agent models to evaluate complex dynamic interactions of organizational entities. These latter aspects will be further worked upon in this paper.

Multi-agent models

Within our systemic accident modelling view for organizational processes, multi-agent modelling plays a key role between a formal description of the structure and relations of an organization, on the one hand, and the stochastic dynamics of interacting organizational agents, on the other hand. Here, incidents and accidents can be considered as emergent phenomena from the variability of the agents’ performance in the organizational context. In agent-based modelling the following aspects are relevant: agents, environment, organization and implementation (see Fig. 1).

- An agent is generally defined as an active object with the ability to perceive, reason and act. To this end, agents may have intrinsic models addressing the agent’s internal representations of the external world (e.g. memory or belief states), motivational and intentional attitudes (e.g. wishes, desires, intentions, goals) and mechanisms for reasoning about its intrinsic states and evaluation of possible behavioural strategies for the future. Agents may interact with other agents, e.g. via collaboration or competition.

- The environment of an agent may include both passive and active entities (other agents). Here, agents act in and receive information from.
- The multi-agent organization specifies the structure and protocols of interactions between agents. These structures may be intentionally designed or they may emerge from repeated patterns of interactions among agents. Organizational structures include hierarchies, holarchies, coalitions, teams, congregations and federations. Depending on the type of an organizational structure, agents are provided different degrees of autonomy at various aggregation levels of the organizational structure.
- An agent-based modelling approach may be supported by a software implementation.

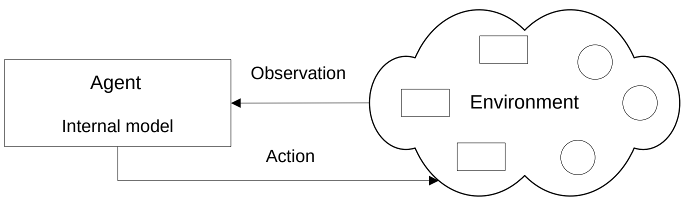

Fig. 1. The classical model of an agent situated in the environment, which includes other agents and passive objects.

As part of the literature review [11], an evaluation of a number of multi-agent design methodologies has been done regarding above multi-agent system characteristics. Table 1 shows the main results of this evaluation; more details can be found in [11]. It follows from this evaluation that the organizational modelling framework of [13] presents the widest repertoire of relevant aspects for multi-agent modelling of organizations. Therefore this framework has been chosen to study the possibilities of organizational modelling in the air traffic safety context of this paper.

TABLE 1
SUMMARY OF CHARACTERISTICS FOR MULTI-AGENT SYSTEM METHODOLOGIES. A '+' DENOTES THAT A CHARACTERISTIC IS ADDRESSED IN THE METHODOLOGY, '-' DENOTES THAT A CHARACTERISTIC IS NOT CONSIDERED.

Method	Environment	Agents		Organization		Implemen-tation
		Internal models	Inter-action	Structure	Dynamics	
[14]	-	-	+	+	-	-
[15]	-	-	+	+	-	+
[16]	+	-	+	+	+	-
[17]	-	+	+	+	-	+
[18]	-	+	+	+	+	+
[19]	+	+	+	-	-	+
[13]	+	+	+	+	+	+

Organizational modelling framework

The foundation of the performance of agents within an organization is specified by the formal organization. This encompasses a definition of the hierarchical structures, interactions, procedures, regulations, goals and performance indicators of the organization as formally described. In other words, it describes the organization as it should be according to its formal definitions. The formal organization can be specified at different aggregation levels, ranging from general regulations for the whole organization to specific prescriptions for particular roles and their interaction with other roles that occur in the executions of work processes. Analysis of processes and relations both at the same aggregation level and across different levels may show potentially safety-critical inconsistencies.

The organizational modelling framework of [13] considers the following four interrelated views to formally describe an organization and link it to a description of performance variability of a multi-agent system:

1. The *organization-oriented view* describes a functional decomposition of an organization by a composite structure of roles at various aggregation levels. These roles are abstracted from particular agents that may fulfil them, e.g. business unit, department, manager or operator. The organization-oriented view describes interactions between roles and specifies the authority relations in an organization: superior-subordinate relations on roles with respect to tasks, responsibility relations, authorization relations and control for resources.
2. The *performance-oriented view* describes the goals of the organizational roles in a goal structure of generic and specific goals. It uses performance indicators as measures of goal achievement for organizational roles.
3. The *process-oriented view* describes tasks and processes in the organization. It specifies static and dynamic relations between processes, e.g. decomposition, ordering and synchronization, and the resources used and produced.
4. The *agent-oriented view* describes the link between the role-based formal organizational model and the agents that are to perform the roles. It formulates agents' types, their capabilities, their behaviour, and the principles of allocating agents to roles. The agent-oriented view crosses the description of the formal organization and the description of performance variability. On the one hand, the performance and interactions of agents are regulated by the formal organization. On the other hand, the dynamics and stochastic aspects of interacting agents contribute to the performance variability in an organization.

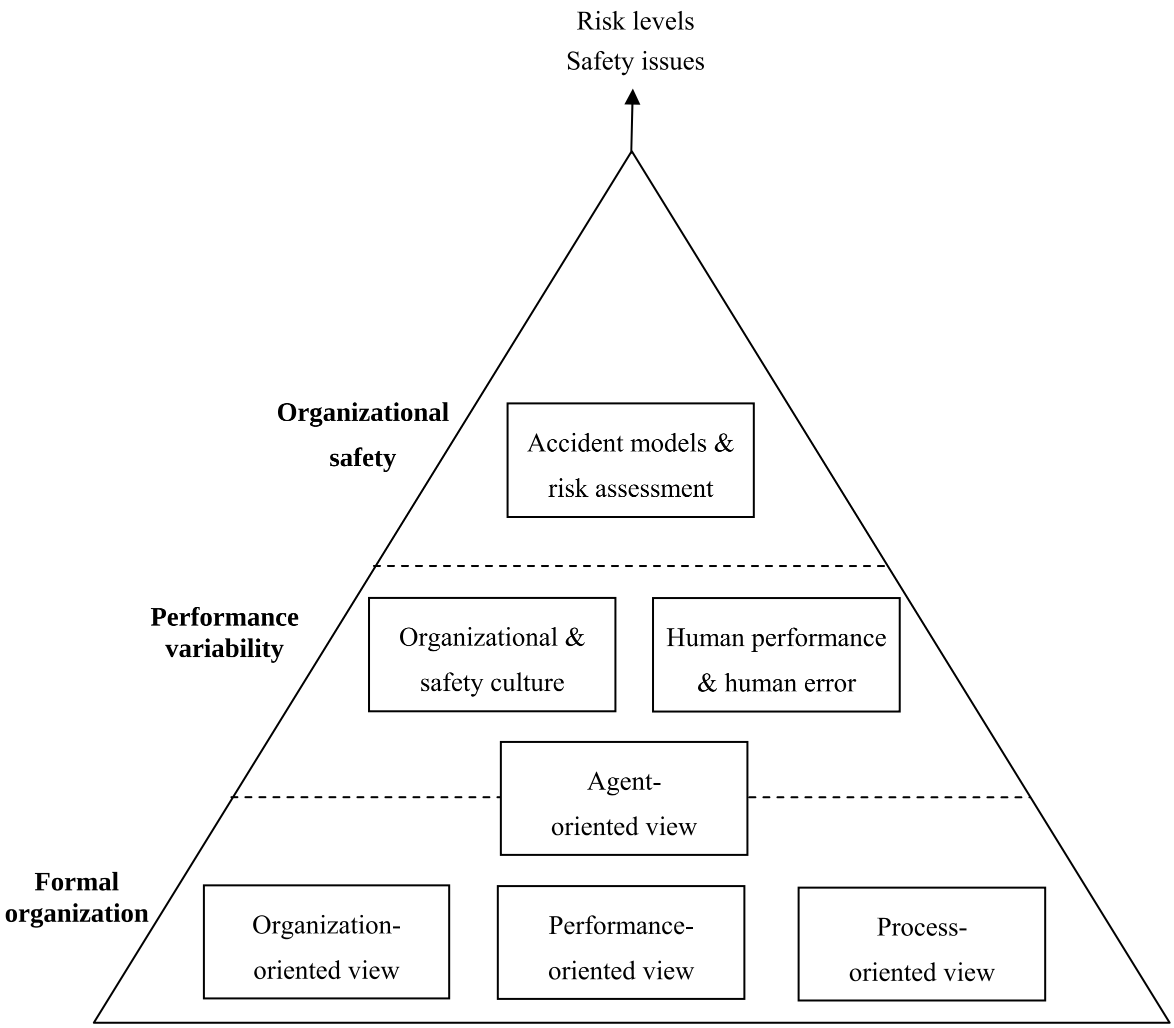

Fig. 2. Organizational safety pyramid.

To illustrate the main aspects of an organizational systemic accident model discussed in this section, we use a three-layered organizational safety pyramid shown in Fig. 2. It describes the main aspects contributing to safety of organizational processes and the evaluation thereof:

- *Formal organization*, using the organization-, performance- and process-oriented views, as well as the agent-oriented view for the connection to the next level;
- *Performance variability*, describing human performance & error, and the moderating effect of organizational & safety culture;
- *Organizational safety*, describing the result of the various sources of performance variability in the organizational context on the development of safety events.

Although this safety pyramid looks similar to the classical safety pyramid of Heinrich [20], it follows from above explanation that the reasoning behind it is quite different from the relation between unsafe acts, incidents and accidents considered in the classical safety pyramid.

III. Organizational Modelling of an Air Traffic Case

In this section we describe the development of an organizational model according to the four views of [13] for an air traffic case on safety occurrence reporting. First we give a high-level description of the case, subsequently the development of the organizational model is described in a number of steps.

High level description of air traffic case on safety occurrence reporting

We study the possibilities of organizational modelling in air traffic for the case of reporting and management of safety occurrences during taxiing operations near an active runway of a fictitious major airport. The runway considered has a complex surrounding taxiway structure, it is in use for take-offs and it may be crossed by taxiing aircraft. Traffic movements on the runway and surrounding taxiways are under control of a runway controller and ground controllers, respectively. In this operational context safety-relevant events may occur, e.g. 'taxiing aircraft makes a wrong turn and progresses towards the runway crossing', 'taxiing aircraft has switched to a wrong frequency' or 'taxiing aircraft initiates to cross due to misunderstanding in communication'. To support safety management, such events should be reported by the involved pilots and controllers. In the air traffic case, we consider that reporting of safety occurrences can be done either via formal organizational lines or via informal coordination. The formal organization considers safety occurrence reporting at the air traffic control centre and at airlines, the informal path considers coordination between air traffic controllers.

The formal safety occurrence reporting at the air traffic control centre starts by the creation of a notification report by the involved controller(s). This notification report is examined and possibly improved by the supervisor. The notification report is processed by the safety investigation unit of the air traffic control centre. The severity of the occurrence is assessed and a description of the event is stored in a safety occurrences database. In the case of single severe occurrences or in the case of a consistent series of less severe occurrences, the safety investigation unit may initiate an investigation for possible causes that may pinpoint to problems in the operations. The results of such an investigation are reported to the operation management team at the air traffic control centre. On the basis of such reporting, the operation management team may decide on a change process of the operation. This may have to be formally approved by the executive management of the air traffic control centre.

The organization of the safety occurrences processing at the airline starts with a notification report created by the pilots. This notification report may be provided to the airline's safety management unit or it may be directly provided to the regulator. The airline's safety management unit examines and potentially improves the report and it informs the regulator about safety occurrences at the airline. The regulator may decide on further investigation of safety occurrences by the regulator itself or by a facilitated external party. Involved airlines and air traffic control centre are informed by the regulator about the investigation results, which may indicate safety bottlenecks in the operation.

The informal safety occurrence reporting path at the air traffic control centre considers that controllers discuss during breaks the occurrences that happened in their control shifts. If they identify potential important safety issues they inform the head of controllers, who is a member of the operation management team. The operation management team may decide on further investigation of the potential safety issue. The results of such investigation are handled as in the formal safety occurrence reporting path.

Model development steps

The development of the organizational model is done in a number of steps specified in Table 2. Steps 1 to 9 are performed subsequently and contribute to one view or the combination of two views. Step 10 may be done after a particular step or after a combination of steps, depending on the type of constraint considered. In all steps, first-order sorted predicate logic serves as a formal basis for defining dedicated modelling languages [21] and temporal relations are specified by the Temporal Trace Language [22].

TABLE 2
OVERVIEW OF STEPS IN ORGANIZATIONAL MODELLING AND THEIR RELATION WITH THE VIEWS CONSIDERED.

Step	Name	View			
		Organization	Performance	Process	Agent
1	Identification of organizational roles	x			
2	Specification of interactions between roles and with the environment	x			
3	Identification of requirements for roles	x			x
4	Identification of organizational performance indicators and goals		x		
5	Specification of resources			x	
6	Identification of organizational tasks and relations between tasks, resources and goals		x	x	
7	Specification of authority relations	x		x	
8	Specification of flows of control			x	
9	Specification of allocation, characteristics and behaviour of agents				x
10	Identification of generic and domain-specific organizational constraints	x	x	x	x

Step 1: Identification of organizational roles

In this step, organizational roles are identified. A role represents a (sub-)set of functionalities of (part of) an organization, which are abstracted from specific agents who fulfil them. Each role can be composed by several other roles; a role that is composed of (interacting) subroles is a composite role. At the highest aggregation level, the whole organization can be represented as one role. The refined role structures may correspond to organizational constructs such as groups, units, departments, managers, operators, etc. Since roles are represented by a composite structure, interactions between roles can be represented at different levels of abstraction.

For the air traffic case, the roles Air Navigation Service Provider (ANSP), Airport, Airline, Regulator and New Operation Design team are considered at the highest aggregation level (see also Fig. 3). The composition of these roles is considered up to two additional aggregation levels. Aggregation level 2 consists of 16 roles that mostly refer to units and teams in the organization (see Fig. 4 for the level-2 roles in the ANSP). Aggregation level 3 consists of 22 roles at the level of single humans (see Fig. 5 for some examples of level-3 roles in the ANSP).

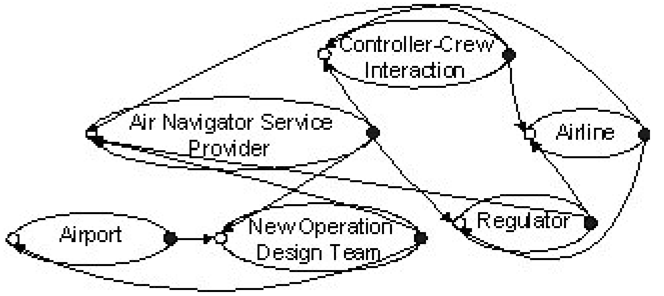

Fig. 3. The interaction relations between the generic roles at aggregation level 1

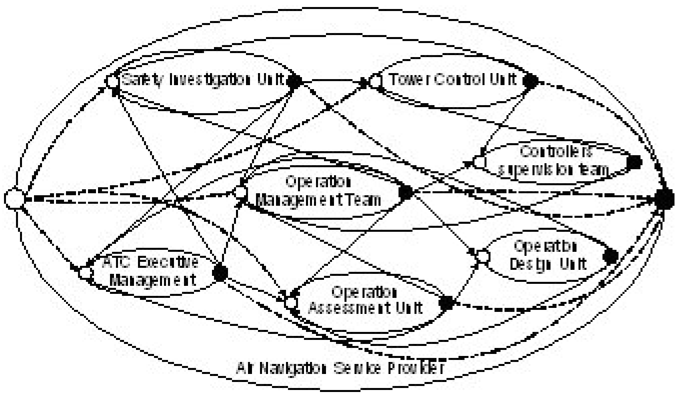

Fig. 4. The interaction relations between the subroles of the role Air Nativation Service Provider at aggregation level 2

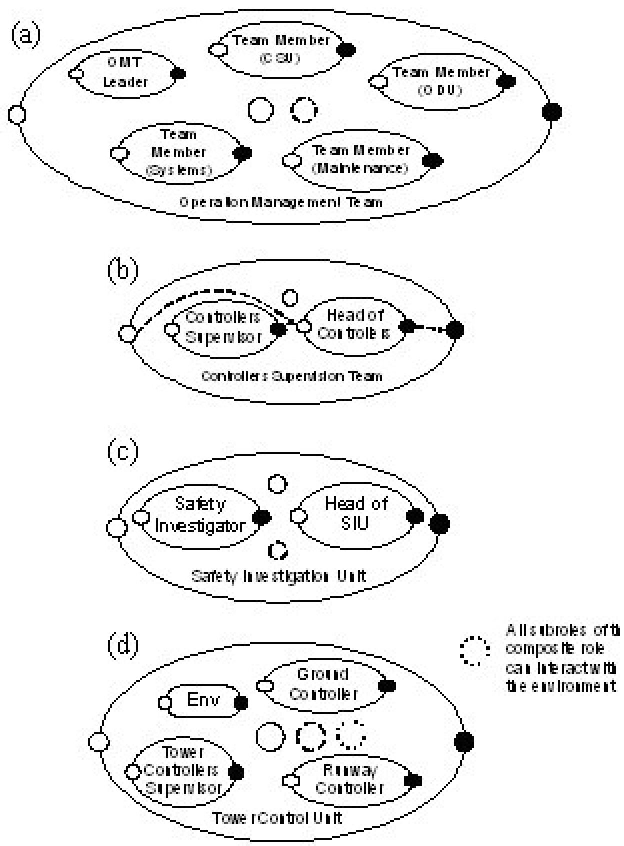

Fig. 5. Examples of interaction relations between the subroles of the ANSP at aggregation level 3: (a) Operation Management Team, (b) Controllers Supervision Team, (c) Safety Investigation Unit, (d) Tower Control Unit.

Step 2: Specification of interactions between roles and with the environment

In this step, interaction relations between roles and with the environment are identified. Furthermore, the vocabulary of interactions (interaction ontology) is defined. Together with Step 1, it contributes to the organization-oriented view.

For the air traffic organizational model, relations between roles exist at the three identified aggregation levels. The interaction relations between the roles at aggregation level 1 of the complete air traffic organization are depicted in Fig. 3. Subroles of the role ANSP are depicted at aggregation level 2 in Fig. 4 and at aggregation level in Fig. 5. Relations between roles at the same aggregation level are represented by interaction links, relations between composite roles and subroles are represented by interlevel links.

Step 3: Identification of requirements for roles

In this step, the requirements for each role at the lowest aggregation level are identified. By execution of this step a relation is created between the specifications of the organization-oriented and the agent-oriented views.

For each role, requirements on knowledge, skills and personal traits of the agent implementing the role are defined.

- Knowledge-related requirements define facts and procedures with respect to organizational tasks that must be well understood by an agent.
- Skills describe developed abilities of agents to use effectively and readily their knowledge for tasks performance. Four types of generic skills are distinguished that are relevant in an organizational context [23]: technical (related to the specific content of a task), interpersonal (e.g., communication, cooperation), problem-solving/decision-making and managerial skills (e.g., budgeting, scheduling, hiring). Requirements on skills can be defined that reflect their level of development, experience and the context in which these skills were attained.
- Personal traits may influence the successfulness of task execution. The traits are divided into five broad categories [24]: openness to experience, conscientiousness, extroversion, agreeableness and neuroticism.

Step 4: Identification of organizational performance indicators and goals

In this step, organizational goals, performance indicators and relations between them and organizational roles are identified. By performing this step a complete specification for the performance-oriented view is specified. Furthermore, this step establishes relations between the performance-oriented and organization-oriented views.

A goal is characterized by the following aspects: name, priority (high, medium, low, etc.), horizon (time interval in which the goal is supposed to be satisfied), ownership (role, agent), perspective (point of view described by the goal, e.g. management, supplier, etc.), hardness (clearness of satisfaction of a goal, i.e. hard or soft), and negotiability (whether negotiation is possible in case of conflicts with other goals). Goals can be refined in goal structure, which defines relations between goals and sub-goals, expressing rules for goal satisfaction. For instance, in the partial goal structure of the air traffic organizational model shown in Fig. 6, goal 3 “It is required to achieve a high level of quality of the internal investigation of a new operation” requires sufficient fulfilment of sub-goals 3.1 “It is required to achieve a high level of thoroughness of the internal investigation of a new operation”, sub-goal 3.2 “It is required to maintain a high professional level of operation analysts” and sub-goal 3.3 “It is required to maintain up-to-date knowledge of norms, standards and statistics used for the evaluation of a new operation”, and goal 3 is supported by goal 4 “It is required to achieve a satisfactory realization of the high level requirements and their refinements in the concept of a new operation”. The developed air traffic organizational model contains 21 goals and 60 sub-goals.

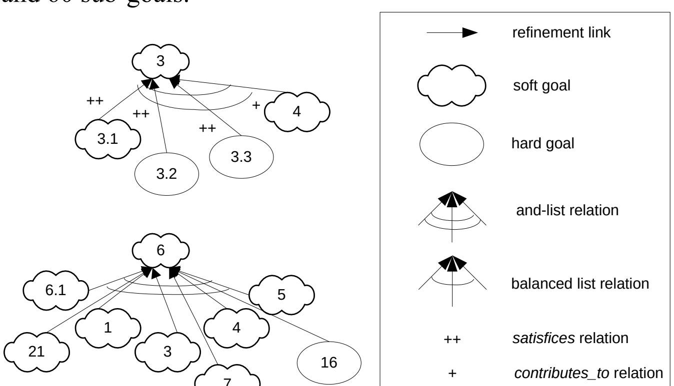

Fig. 6. Part of the goal structure in the air traffic organizational model.

Performance indicators are goal-associated quantitative or qualitative expressions of the state/progress of a role or agent. Performance indicators can be soft or hard. A soft performance indicator is difficult to measure directly and is usually specified by a qualitative expression, e.g. customer’s satisfaction, company’s reputation, employees’ motivation. A hard performance indicator is well measurable and usually expressed quantitatively, e.g. number of customers, number of landing aircraft, or average time to cross an active runway. A number of relations can be defined between performance indicators: causal, correlation and aggregation. Fig. 7 shows graphical representation of the relations between performance indicators in the air traffic organizational model. Here, examples of the types of relations are:

- Causality – indicator 1.1 “The completeness and accuracy of the identification of high level safety-related requirements for a new operation from all parties involved into the operation” causes a positive change of indicator 2 “The level of safety of a new implemented operation”;
- Correlation – indicator 9 “The development and assessment time of a new operation” correlate positively with indicator 3 “The level of quality of the internal investigation of a new operation”;
- Aggregation – indicator 9 “The development and assessment time of a new operation” is an aggregation of indicator 9.2 “The development time of the concept of a new operation”.

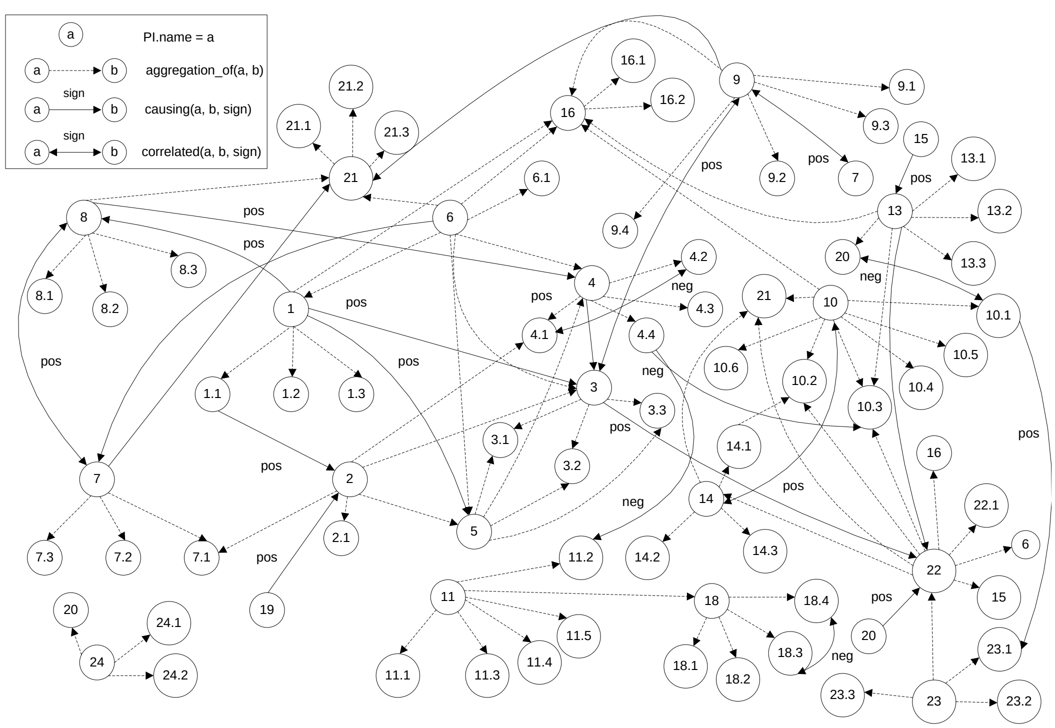

Fig. 7. Relations between the performance indicators in the air traffic organizational model.

Step 5: Specification of resources

In this step organizational resources are defined. Resources describe a wide range of materials and data, such as tools, supplies, components and digital artefacts. Resources are characterized by name, category (discrete/continuous), measurement unit, expiration duration and amount. This step is part of the process-oriented view.

Examples of resources in the air traffic case are aircraft, radar system, incident database, incident investigation report and R/T system.

Step 6: Identification of organizational tasks and the relations between tasks, resources and goals

This step identifies organizational tasks, their characteristics and relations, and defines relations between tasks and resources. Furthermore, this step relates each task to a goal and thereby establishes a connection between the process-oriented view and the performance-oriented view.

A task represents a function performed in the organization and is characterized by a name and by minimum and maximum durations. Tasks can range from very general to very specific. General tasks can be decomposed into more specific ones using AND- and OR-relations and thereby form hierarchies. For every task it is indicated to which organizational goals they contribute. For every task it is indicated which kinds and quantities of resources it uses, consumes and produces.

The model contains 15 general tasks and 26 specific tasks. Examples of tasks in the air traffic case are: creation of a notification report, preliminary processing of a notification report, making decision about the investigation necessity based on the provided notification report, investigation of the occurrence based on the notification report.

Step 7: Specification of authority relations

In this step authority relations (formal power relations) of an organization are identified: superior-subordinate relations on roles with respect to tasks, responsibility relations, control for resources, authorization relations. Authorization and responsibility relations are defined with respect to task execution, task monitoring, consulting, technological decision-making and managerial decision-making.

In the model responsibilities are defined for all tasks. For example, the following responsibilities of roles are defined with respect to the task “Investigation of the occurrence based on the notification report”: for task execution and technological decisions the Safety Investigator is responsible, for monitoring, consulting and managerial decisions the Head Safety Investigation Unit is responsible.

Step 8: Specification of flows of control

In this step the dynamic part of specification for the process-oriented view is described. This is achieved by the definition of workflows that represent temporal execution sequences of processes of an organization in particular scenarios. Fig. 8 shows an example of the workflow for the processing of incident reporting by a controller.

Step 9: Specification of allocation, characteristics and behaviour of agents

In the context of organizational modelling, the performance variability in an organization is the result of the behaviour of agents that are allocated to organizational roles. In Step 9, the characteristics and behaviour of agents allocated to organizational roles are described. The characteristics describe knowledge, skills, personal traits and internal goals of the agents.

In the context of the air traffic case, the following types of agents are defined: Controller, Controller Manager, Pilot, Regulator, Safety Investigator, and Manager. For example, the agent type Controller may have the following characteristics: decision-making skills, passed a rigid medical examination, number of years of college education before initiation of ATC training, knowledge of the air traffic management system and flight regulations, number of hours of computer training, number of hours of air traffic control training, listening and communication skills, ability to stand stress, and short-term memory capabilities. By assigning different values to the identified characteristics different instances of the agent type Controller can be specified.

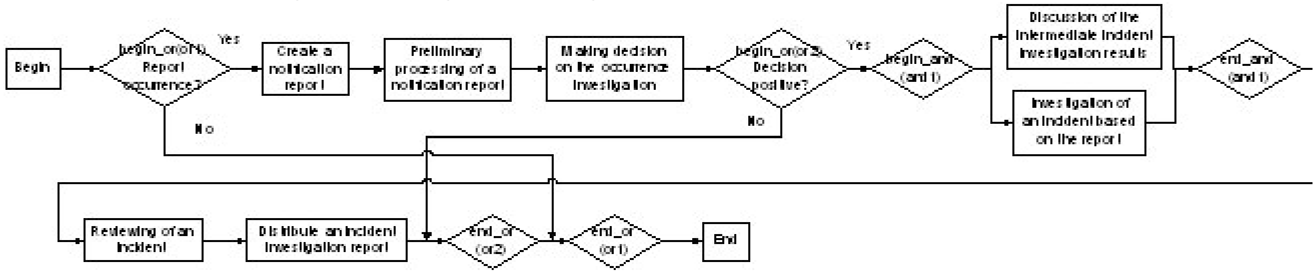

Fig. 8. : Workflow for management of controller incident reporting.

The behaviour of agents is considered to be goal-driven. In the case study the agents' goals are consistent with the organizational goals. The internal states of agents allocated to organizational roles are represented as beliefs. A belief of an agent is created based on one of the following events:

- observation from the environment – a belief state is generated after the agent observed some occurrence in the environment;
- communication provided to/obtained from another agent – belief states are changed for the agents involved in the communication;
- action performed by the agent in the environment – a belief state is changed after the agent performed an action.

In addition to the general belief update functions, specific rules for the belief states of agents in the air traffic organizational model are defined.

Step 10: Identification of generic and domain-specific organizational constraints

Within every view and across views of the organizational modelling framework, a set of structural and behavioural constraints can be defined (see Fig. 9). The purpose of the formulation of the constraints is to define key markers for desired behaviour in the organization. The satisfaction of the constraints of the organizational model can be evaluated in analysis and simulation of the model. The constraints are divided in two groups:

1. Generic constraints that need to be satisfied by any specification of a view or by a combined organizational specification. Generic constraints can be structural integrity and consistency constraints based on the specification rules of the composition, or constraints imposed by the physical world.
2. Domain-specific constraints are imposed by the organization, external parties or the physical world of the specific application domain.

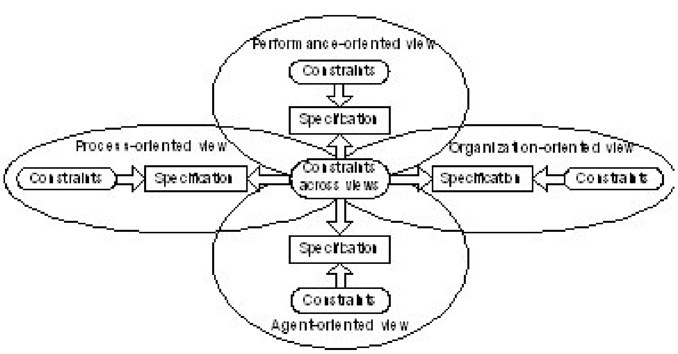

Fig. 9. Constraints in the organizational modelling framework.

Examples of constraints in the various views for the air traffic case are:

- Generic structural integrity constraint in the performance-oriented view: "If performance indicator A causes a positive change of indicator B, and indicator B causes a positive change of indicator C, then indicator A causes a positive change of indicator C".
- Generic constraint in the process-oriented view: "Not consumed resources become available after all processes are finished".
- Domain specific constraint in the process-oriented view: "Each active runway should not be used by more than one aircraft at the same time".
- Generic constraint in the organization-oriented view: "Each role may be a subrole of one complex role at most".
- Domain specific constraint in the organization-oriented view: "The pilots of the crew should verbally share relevant information with each other".
- Generic constraint in the agent-oriented view: "To be allocated to a role, an agent should possess all the required knowledge and the development levels of skills, and the required traits".
- Domain specific constraint over combined process-oriented, organization-oriented and agent-oriented views: "Each observed incident/accident should be reported by a controller".

IV. Organizational Analysis Results

For analysis of the developed organizational model two types of techniques can be applied [13]:

1. Checking the consistency and correctness of organization models. This analysis type focuses on verification of the model specification for the particular views. By applying this analysis type, the correctness of a specification of a particular view with respect to the corresponding set of constraints can be established. For this analysis, techniques based on first-order sorted predicate logic are used.
2. Verification by simulation. The second type addresses the validation of constraints on single or combined specifications of different views by simulations. In such simulations, agents are allocated to particular organizational roles.

Next, the types of results that can be achieved by these analysis techniques are presented for the four organizational modelling views.

Organization-oriented view

The organization-oriented view identifies sets of generic consistency constraints on both interaction structures of roles [25] and on formal authority relations [26] between roles. Examples of possible conflicts on interaction relations between roles include:

- Roles involved in the execution of a task do not interact (may be a problem when they need to interact).
- A communication path does not exist at all when it should exist.
- The role which supervises the execution of some process

should interact with the role performing the process.

Examples of possible conflicts on authority relations between roles include:

- A role has more than two direct superior roles (at the same level of the authority hierarchy); this may cause a problem when these roles have different opinions on a task-related decision.
- Conflict between a goal requiring some level of autonomy for a role and a strict authority structure that does not allow realizing this goal.
- Responsibility/authorization for some aspect of a task is provided to a role for some time interval and after finishing this interval the role acts as if the responsibility is still provided.

Performance-oriented view

For analysis of the performance-oriented, view consistency checks can be performed for the goal and performance indicator structures [27]. For example, goal 3 “It is required to achieve a high level of quality of the internal investigation of a new operation” and goal 9 “It is required to minimize the development and assessment time of a new operation” are in conflict. This conflict has been detected since the corresponding performance indicators “Quality of the internal investigation of a new operation” and “Development and assessment time of a new operation” are related by a positive causality relation, and the corresponding goal patterns are based on opposite types of functions to either maximize or minimize the performance indicator.

Process-oriented view

In the process-oriented view structural consistency constraints are defined for workflow, task and resource hierarchies [28]. Automated algorithms are available for the verification of these constraints on process-oriented specifications.

The verification of the correctness of a specification is performed during or at the end of the design process, depending on the type of constraint. Some domain-specific constraints might not (yet) be satisfied for incomplete specifications. The designer can choose when they should be checked. The syntactical check of a specification and the verification of generic constraints are performed at each design step.

Examples of types of inconsistencies that can be identified by these techniques are:

- A process is not finished before a dependent process has commenced.
- Processes try to share a non-sharable resource (e.g. a runway).
- A resource is located at a non-accessible place.
- A pilot is assigned to multiple simultaneous flights.
- Particular information types may not be used by tasks (security/privacy).

Agent-oriented view

In the agent-oriented view, the dynamic interactions of agents allocated to the roles in the organization are evaluated in varying contextual conditions. For the air traffic case described in Section 3, simulation models have been developed for the formal and informal reporting of incidents during taxiing operations [29]. These simulation models represent the behaviour of agents for the roles considered (e.g. controllers, pilots, safety investigator) in the context of six types of safety occurrences that may happen during taxiing. The events considered are:

a. Aircraft rejects take-off as result of a runway incursion;
b. Taxiing aircraft stops progressing on the runway crossing only after the stopbar and due to a call by the runway controller;
c. Taxiing aircraft makes wrong turn and progresses towards the runway crossing;
d. Taxiing aircraft makes wrong turn and progresses on a wrong taxiing route that is not a runway crossing;
e. Taxiing aircraft has switched to a wrong frequency;
f. Taxiing aircraft initiates to cross due to misunderstanding in communication.

In the model, the formal and informal handling of these events may lead to a start of a safety investigation and thereby to the identification of safety-critical aspects in the operation. In both the formal and informal approaches, the severity of the event has impact on the decision to initiate an investigation; in particular, less severe events require more occurrences.

TABLE 3
RESULTS OF THE AGENT-BASED SIMULATIONS

Event	Fraction of traces with start of investigation given the event type		Mean time before start of safety investigation (days)	
	Formal	Informal	Formal	Informal
a	22%	21%	155	135
b	5%	15%	168	124
c	28%	50%	195	150
d	0%	0%	-	-
e	0%	3%	-	279
f	45%	11%	186	185
total	100%	100%	181	150

For the formal and informal cases, 100 simulations have been performed with 12 operational hours per day and a maximum simulation time of 3 years. Main results of these simulations are shown in Table 3. The results shown are the fractions of cases in which an investigation is initiated given a sufficient number of occurrences of a particular event and the mean time until start of the investigation. For both the formal and informal handling of safety occurrences in all simulation traces a safety investigation is initiated, but the mean time until start of the investigation is 181 days in the formal case, whereas it is 150 days in the informal case. A main reason underlying this difference is that events like *b* and *c* are often recognized by both ground and runway controllers and thus feed common situation awareness on safety-critical aspects in informal discussions, whereas such events are just single occurrence reports in the formal incident reporting case.

V. Discussion

In this paper we have presented the first results of a new approach for systemic accident modelling of organizational processes in air traffic, based on the organizational modelling approach of [13]. This systemic modelling approach provides a broad scope description of the 'system' (i.e. the organization) and the variance in its performance. The analysis of the model is focussed on obtaining inconsistencies in the model and evaluating emergent safety-relevant characteristics. Systemic accident modelling can be contrasted with sequential or epidemiological accident modelling approaches, which merely use influencing factors to represent the effect of organizational factors on risk levels.

The organization is modelled according to four interrelated views that account for a variety of organizational aspects. Three of these views have a distinct focus on the formal organization and describe the organizational structure (roles, their interactions, authority relations and resources), the organizational behaviour (processes in an organization and their relations), and the organizational goal-related performance (goals, performance indicators). The fourth view describes the link between the role-based formal organizational model and the agents that perform the roles. The performance of the agents is determined by the formal organization, but it is also influenced by the stochastic dynamics of interacting agents. Variations in the agents' performance (e.g. tasks are done slower/quicker, tasks are omitted, tasks are done in varying order, etc.), variations in environmental conditions and variations in interactions between agents all have effect on the overall performance of the organization. With these four interrelated views a broad scope of organizational modelling can be achieved.

It follows from the literature survey [11], that the modelling approach used has the broadest scope of the multi-agent modelling methods identified. In relation with the safety literature, we note that many risk assessment methods have a purely functional focus, which only consider malfunctioning of functions in an operation. It is questionable whether methods with such a limited focus can support effective risk assessment of organizational processes. In contrast, the methods presented in this paper also include functional aspects in the process-oriented view, but they extend the focus extensively to the four interrelated views on organizational modelling.

For broad scope organizational modelling it is important that the methods well support managing a potentially complex model. An issue herein is the level of scalability of the modelling methods. In the approach portrayed, the organization can be modelled at various aggregation levels and particular aspects of the model can be included or excluded at the different aggregation levels, depending on the goal of the study. Modelling tools support automatic expression of relations between model aspects at high and low aggregation levels. Explanatory ease and usability of the modelling methods is supported by various graphical interfaces and the application of generic templates.

This modelling approach provides a framework to address well-known important contributors to the safety in an organization: human performance/error and organizational/ safety culture. The formal organizational model provides a broad scope description of organizational aspects that form the working context of the humans in the organization (e.g. tasks, hierarchy, responsibilities and goals). This working context also addresses aspects of organizational/safety culture, such as information streams, working conditions, management involvement and safety-related behaviour. The agent-oriented view provides the means to describe (the variability of) human performance in interaction with other agents and in the working contexts of the agents. Here, the effect of organizational/safety culture can be described by its influence on the level of performance variability.

The modelling approach supports safety assessment by identification of misconceptions or inconsistencies both at the level of the formal organization for the range of views considered, and at the level of agents by the evaluation of safety-relevant performance in multi-agent simulations. The presented results show various forms of inconsistencies and indicate the potential strength of informal coordination for safety occurrence reporting. It is noted that the validity of the model has not been evaluated. The prime goal in the research phase presented is the inventory of the possibilities of organizational modelling and the links with safety assessment, rather than the particular outcomes of the model analysis.

VI. Future Research

The study presented in this paper is a first step towards multi-agent systemic accident modelling for organizational processes. This first step has identified a new approach and clarified the types of results that can be attained.

The proposed follow-up research aims to lay more direct links with the needs in safety cases for organizational processes and to develop an advanced organizational safety model that addresses those needs. Next year's research can be organized along the steps in the original project planning [30].

The identification of objectives for further organizational modelling is done in WP3 'Identification of application and analysis objectives'. The identification of objectives for organizational modelling will be based on needs from risk assessment cycles and safety case development. This may include the identification of objectives for laying explicit relations with human performance/error and organizational/safety culture. We intend to further increase the validity of the organizational safety model by incorporating more specific knowledge of relevant organizational processes. To assure a sufficient knowledge base we will consider in WP3 what issues should be considered in the air traffic case for the advanced organizational model.

In WP4 'Organizational safety model & simulation of advanced air traffic application' the advanced organizational model will be developed in the context set. Building forward on the results achieved, more specific knowledge will be integrated in the organizational model. Model analysis and simulation results will be achieved for the advanced organizational model.

VII. Publications in the Project

The first year of research has resulted in reports [11][29] and a research paper published at the EUROCONTROL Safety R&D Seminar 2007 [31]. The project has contributed to the PhD research of Alexei Sharpanskykh and associated research papers [13][26][28][32][33][34].

Acknowledgement

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Satisficing Game Theory for Distributed Conflict Resolution and Traffic Optimisation: a Simulation Tool and Experimental Results

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***Abstract*—In the current, centralized approach to Air Traffic Control (ATC) air traffic controllers are responsible for the safe and efficient flow of aircraft. This situation would change with the introduction of Airborne Self-Separation as a distributed and scalable approach to ATC. The major technological challenge that must be tackled to make Airborne Self-Separation a viable alternative to the traditional controller-based approach is to devise a safe and reliable technology to solve conflicts and improve global performances in an uncontrolled environment. In this paper we introduce an algorithm that applies Satisficing Game Theory (SGT) to solve conflicts in the framework of an overall optimisation of the traffic flow. This algorithm is inspired by the work presented in [1]. The paper presents the first results we collected by running a software tool which simulates the behavior of the SGT algorithm in a 3D environment, using air traffic samples provided by the Italian air traffic service provider (ENAV). These results are the starting point of a further enquiry to explore the actual impact of the introduction of such a technology in a realistic ATC environment.**

I. Introduction

In today's Air Traffic Management system, the responsibility for maintaining a safe and efficient traffic flow is entirely delegated to controllers, who issue flight instructions to pilots as well as grant or deny authorizations to apply specific procedures. Because of the capacity limitations of this approach, several possible alternatives and complementary approaches are currently under investigation. *Airborne Self-Separation* [5] or *Free Flight* in less recent literature [3], [4], is an operating environment in which pilots are allowed to select their route in real time and without any external control by air traffic controllers, and therefore they bear more responsibility for the safe and efficient conduct of the flight.

The advantages of Airborne Self-Separation broadly conceived will be twofold. On one hand it should lead to reduced costs, better fuel consumption and increased capacity. Self-optimisation by the airlines could be more effective than any global optimisation that can be performed by a human controller (see [2]), because different airlines might give higher priority to different parameters which depend on company strategy or other factors only known to the airline and crew. On the other hand, in the current centralized, controller-based approach there are difficulties in scaling up to cope with the increasing volume of future air traffic while keeping or improving air traffic safety (air traffic is predicted to grow exponentially at a rate of 5 to 6 percent per year [6]). If appropriately coupled with necessary improvements in automation, Airborne Self-Separation could reduce airline operating costs and controllers' workload, therefore resulting in an increase in efficiency without adversely affecting the safety of air travel.

A. Conflict resolution for Airborne Self-Separation

One of the most important safety issue for air traffic in general, and for Airborne Self-Separation in particular, is conflict resolution. Current procedures almost entirely rely on the controller's ability to coordinate and organize the flow of air traffic, with the help of standardised procedures, data presentation and supporting tools. Automation plays only a limited role, and rightly so: an automatic, centralized ATC system would have to deal with potentially thousands of aircraft spread over a vast geographic area to ensure resolution of all possible conflicts. As the number of planes increases, the complexity of conflict resolution grows and quickly becomes computationally intractable. This is only made worse by the fact that such a system should operate under tight time constraints: actions for every single aircraft must be decided and taken often in a matter of minutes, if not seconds. Similarly, the possibility that a single failure in the central control unit could disable a significant portion of the centralized system creates a highly undesirable risk.

One common misconception is that, since pilots will be given more freedom to decide their routes, and to dynamically alter them without external control, Airborne Self-Separation will result in a "chaotic flight environment", and therefore one in which there will be fewer conflicts. The truth is that one kind of constraints (induced by instructions issued by controllers to organize the air traffic flow into safe and well-known patterns) will be replaced by another kind of constraints (like fuel consumption, timeliness, customers satisfaction and comfort, environmental impact etc). In pursuing their own preferred routes, aircraft will again congregate on given paths, and even more on given congestion points like airports, or Airborne Self-Separation space "entrance gates" (see [7]) . In any possible future Airborne Self-Separation scenario, conflict resolution remains the single most important issue.

In a Airborne Self-Separation environment which implements airborne separation, every aircraft is responsible to take any measure necessary to avoid conflicts with other aircraft. Every plane is pursuing its own route maximizing its own optimality function, be it fuel consumption, timeliness, or any other factor depending on the airline policy. In a sparsely populated airspace, the action of a single aircraft seldom influences other aircraft' route, therefore the actions taken by a single aircraft only have consequences limited to the aircraft itself. On the contrary, in a crowded airspace any maneuver of a single aircraft (to avoid another aircraft, or to achieve its goal with respect to its own optimality function) may entail a domino effects of corrective or avoidance maneuvers by other aircraft. That is, a single, "locally optimal" maneuver can yield an overall degradation of the system in terms of global average delays, fuel consumption or some other parameter that measures some desirable property of the whole set of aircraft involved. In an ideal world, conflict resolution must guarantee both safe separation between aircraft, and the optimisation of some parameter for the whole set of aircraft engaging the considered airspace. The combination of these two tasks, especially in airspaces where tens of planes are flying, may lie beyond the possibilities of any human-centered centralized control.

B. *Collective Intelligence: a new conceptual framework*

We plan to address the problem of conflict resolution in a Airborne Self-Separation airspace with an approach inspired by the emerging framework of Collective Intelligence (COIN, see [8]). This formal framework is designed to address situations where there is no centralized control and where there is a clear global objective function that needs to be optimized. More specifically, we might isolate the following characteristics for problems which can be tackled by Collective Intelligence techniques:

- the problem can be modeled by means of a collection of agents;
- agents do not need centralized control;
- each agent acts independently from each other, pursuing its own specific objective, and maintaining only a limited vision of the overall situation;
- there is a well-specified (i.e. mathematically defined) global objective;
- agents need to coordinate to achieve this objective;
- agents are adaptive, i.e. they dynamically react to changing conditions of the environment.

Within this framework, the "intelligent" behavior of the whole system does not result from careful top-down off-line algorithmic planning; it is rather an emergent property of the system as a whole, in which each agent, while pursuing its own limited goals and locally interacting with other agents, maximizes the given optimality function for the system. This new emerging paradigm has already been proved successful in a number of other technological domains (e.g. packet routing, transport logistics, automated car driving, see [8] for a survey on possible applications). Benefits resulting from this approach are manifold. First of all, by relying on computation distributed among several independent agents, the risk of catastrophic failures for the system is largely subdued. In the traditional, centralized approach to control, a single failure occurring in the central control unit might "leave in the dark" any process (in our case, any plane) which depends on it. On the contrary, the intrinsically distributed and adaptive nature of Collective Intelligence agents allows for a higher degree of robustness and dependability for the whole system. The failure of a single node does not entail the failure of the whole system, and other agents can more or less quickly adapt to the new configuration. Distributed computing also allows for more efficient computation of possible solutions to the optimisation problem. Although the solution provided might be only sub-optimal, it usually largely outperforms any approach purely relying on human intervention, and it can be achieved with cheap computational resources in real time.

It is apparent that the problem of conflict resolution for Airborne Self-Separation is particularly well suited to be tackled within the Collaborative Intelligence paradigm. In a Airborne Self-Separation environment, every aircraft acts as an agent pursuing its own goals (shortest route, fuel consumption, timeliness) as independently as possible from other agents engaging the same airspace. However, when a potential conflict occurs, the planes involved must coordinate among themselves and with others in their immediate vicinity to agree on conflict resolution maneuvers which are minimally expensive for the whole set of aircraft. As we will see in the next section, it is possible to rigorously address this issue within the framework of Collective Intelligence, by encoding some form of "altruistic behavior" among the agents, therefore allowing for a compromise between local optimal choices and overall performance of the system.

II. Satisficing Game Theory Basics

Much of the recent research in ATM, see [9] and [10] for a review, has focused on solutions for conflict avoidance that are based on fixed sets of rules that dictate actions based on situational geometry. This approach can achieve arbitrarily good performance in a fixed scenario, such as two intersecting flows of aircraft described in [11], but acceptable performance in arbitrary situations cannot be guaranteed. Both centralized and distributed algorithms have been proposed to aid in conflict resolution, but previous schemes involve little if any cooperation. At a minimum, a suitable distributed solution should have several characteristics: (1) the aircraft must coordinate their decisions in avoiding collisions; (2) the avoidance maneuvers must be generally applicable and not limited to specific geometric situations; (3) the avoidance maneuvers must ensure an overall traffic optimisation, in terms of aircraft trajectories and global delays; (4) the approach must be realistic and not oversimplify the problem; (5) the solution must scale to high traffic densities.

Collective Intelligence algorithms can effectively and efficiently resolve most conflicts, even with high traffic densities. In particular, Satisficing Game Theory (see [12]) is based upon the following key concepts: (1) rather than seeking the *optimal* solution for the group and all agents simultaneously, satisficing agents simply obtain an *adequate* solution; (2) agents determine the adequacy of a choice by comparing two different utility functions representing respectively the benefits (selectability) and the costs (rejectability) of the considered choice. Thus, a choice is acceptable if the benefits outweigh the costs. This approach allows individuals or groups to condition their own preferences on the preference of others, therefore enabling a truly collaborative approach to conflict resolution. By exchanging the information and goals of each agent, cooperation among agents can be realized even in a completely distributed system.

A. The algorithm (2D case)

In testing the algorithm of [1] for the 2D case, we assume that all aircraft fly at the same altitude and at the same constant speed. At each second, each aircraft has to choose among one of five directional options: flying straight, moderate turn on the left, sharp turn on the left, moderate turn on the right and sharp turn on the right.

The first step in applying SGT is creating *influence flows*, i.e. oriented graphs such that an arc exists between node A and node B if and only if the directional choice of aircraft A will have an impact on the directional choice of aircraft B. In order to do that, at each time step each aircraft exchanges information with all other aircraft within a 50 nmi radius. This information includes: current position, destination, actual heading, flight time and delay, relative to an unobstructed straight line flight.

Each aircraft ranks the set of viewable aircraft (within 50 nmi), according to: proximity to destination, delay (greater delay, higher rank), flight time (longer flight time, higher rank). On the basis of this ranking, for each aircraft X_i we define its *priority set* P_i, i.e. the set of all viewable aircraft with ranking higher than X_i that could conflict with X_i itself (for some heading choice). This set is also known as the set of X_i's *parents*. The directional choices of X_i will be conditioned on the preferences of all the aircraft in its priority set P_i.

On the basis of the exchanged information, each aircraft computes the *rejectability* p_{R_i} and *selectability* p_{S_i} of each directional choice u_l^i, and selects the directional option $u_{l*}^i \in U$ that maximizes the difference between the selectability and rejectability utilities:

$$u_{l*}^i = \arg\max_{u_l^i \in U}(p_{S_i}(u_l^i) - p_{R_i}(u_l^i)) \quad (1)$$

Loosely speaking, each "satisficing agent" is looking for the highest gain, with the lowest risk.

In the ATC context, the rejectability function reflects the concern about the safety of the considered aircraft: it indicates the degree of risk of each directional option, i.e. how much it is likely to lead to conflicts with higher priority aircraft. In order to compute the rejectability, each aircraft compares the linear projection of each of its directional options with linear projections of current headings of all aircraft in its priority set P_i. Each projected conflict adds a weight to that option, depending on distance in time and severity of the missed separation (distance to collision). After all the parents are considered, the weight of each option is normalized over the option space. The mathematical definition of the rejectability increases the (negative) value of the option that leads to loss of separation, with higher weight assigned to those which are supposed to occur sooner in time.

The selectability function reflects goal achievement, namely (in our ATC context) reaching the destination. In contrast with rejectability, selectability is influenced by the preferences of other agents. Thus, we have two distinct components for the selectability: the base selectability σ_{S_i}, which accounts for agent X_i heading preferences, and ρ_{S_i} which accounts for other viewable agents preferences.

The base selectability σ_{S_i} of each directional option is determined by the difference with the desired heading of the aircraft: if an option takes the aircraft more directly to its destination, it will have a higher base selectability.

The parent selectability ρ_{S_i} is computed using the base selectability of all higher-ranked aircraft to approximate their full selectability. We take into account (in a simplified, but effective way) the preference and the "desires" of all the parents of our aircraft: if one of them strongly prefers a direction that will lead to a missed separation, the current aircraft will lower its selectability for those directional options that will lead to it. This allows for cooperation and "conditional altruism", as previously mentioned.

Finally, the selectability mass function is formed by the convex combination of base and parent and selectability:

$$p_{S_i}(u_l^i) = \lambda\sigma_{S_i} + (1-\lambda)\rho_{S_i} \quad (2)$$

where, in our simulation, we use $\lambda = 1$ if the considered aircraft has no parents, i.e. $|P_i| = 0$, otherwise $\lambda = 0.001$. After computing rejectability and selectability, each agent chooses the heading change to perform, following the decision rule described above.

B. System performance metrics

In order to test the decentralized satisficing algorithm, we consider different performance measures: the most important is the absence of missed separations, called Separation Assurance. We compute it as a function of varying traffic densities and of different traffic scenarios. We also take into account the System Efficiency which is defined as the degree to which an aircraft is able to follow its ideal flight path. In order to compute it for the whole system, we perform the overall average

$$SE = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{t_i}{t_i + t_{d_i}}\right) \quad (3)$$

where t_i is the ideal flight time for aircraft i and t_{d_i} is the delay time. Conflict resolution maneuvers will cause each aircraft to deviate from each ideal path, increasing costs and adding delays. For an algorithm to be successful, conflicts must be avoided while maintaining high efficiency.

C. Variations and generalization

In order to achieve a better realism, we are implementing several generalizations of Hill's algorithm: the most important is the possibility to perform changes in altitude, therefore modeling in a more realistic way a 3D space. The aircraft can change level at each time step, by adding two other directional options: up and down. We are still testing the effect of that important change on the algorithm performance: on one side allowing changes of level obviously is an advantage in avoiding conflicts, on the other side adding a degree of freedom lead to a higher level of complexity in the interaction among aircraft.

Another important variation in our simulator is the introduction of different speeds for different aircraft models, as in the real world. We also include the capability of managing the presence of bad weather conditions or no-flight zones, introducing some forbidden areas and adding an higher weight in the rejectability function for the directional option that will lead to them.

We are modeling real airspace more realistically, introducing airport scenarios, real traffic flow data, provided by ENAV, the Italian Agency for Air Navigation Services, and interfacing with ENAV simulators. Finally we will test more deeply the stability and the scalability of this algorithm, considering also another important measure of performance, often used in literature [1]: the System Stability SS, that is a measure of the extent to which conflict resolution maneuvers create new conflict that will require additional resolution maneuvers. The SS is defined as

$$SS = \frac{|A_1|}{|A_2|} \tag{4}$$

where A_1 is the set of conflict alerts if all aircraft were to fly straight-line paths to their destination and A_2 is the set of conflicts alerts arising where conflict resolution maneuver are employed.

III. SMARC: A 3-D SOFTWARE DEMONSTRATOR

In order to perform a sequence of quantitative simulations, running the algorithm on a set of test cases, we developed a software capable of rendering a three-dimensional animation of arbitrary flight scenarios.

The user can describe a flight scenario by specifying both the global parameters of the simulation (such as proximity radius, near miss radius and collision radius) and the features of each involved flight (such as the starting point, the destination point and the speed).

The computation of the simulation is performed offline (i.e. not in real time), and then graphically rendered in playback mode. This allows for both a more precise rendering in terms of timing accuracy and more freedom in terms of different playback options (such as reverse-order or fast-forward at arbitrary speed, o random jump across the whole time-line). A step-by-step playback mode is also available. During the playback, beside the graphical visualization, it is also possible to display the complete state of the ongoing flights in numerical terms (position, flight time, distance from the target, delay, priority).

The time resolution of the rendering is the same as the simulation: one second in the simulation time.

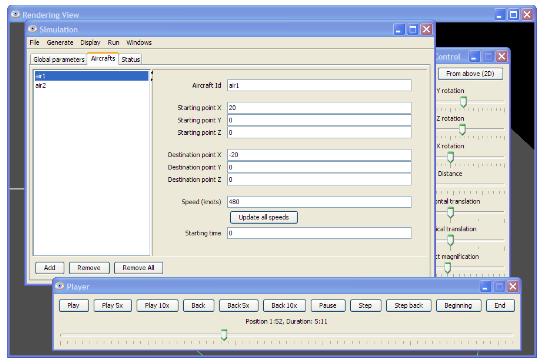


Fig. 1. SMARC control panel

The 3D visualization can be rotated along each axis, and uniformly scaled; a special predefined setup display a bidimensional view "from above", which resembles a traditional "radar view", and may result clearer for the viewer for simulation scenarios where the flight height is less significant.

Optionally, proximity areas and separation areas may be depicted as colored circumferences; optimal and actual path may be displayed as well. Conflict sets may be highlighted when they arise.

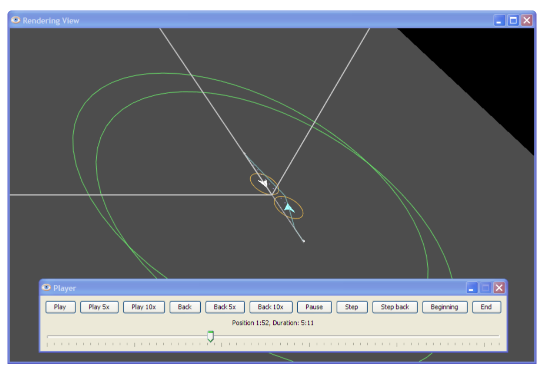


Fig. 2. SMARC Simulation window (3D view)

Some typical starting test configurations (such a random distribution on a spherical surface, or different cross patterns) can be automatically generated.

The software is written using the Java programming language (Java SE 6) in order to ensure maximum portability among different computing platforms. 3D rendering is performed using open source software libraries able to interface any OpenGL-capable graphic hardware.

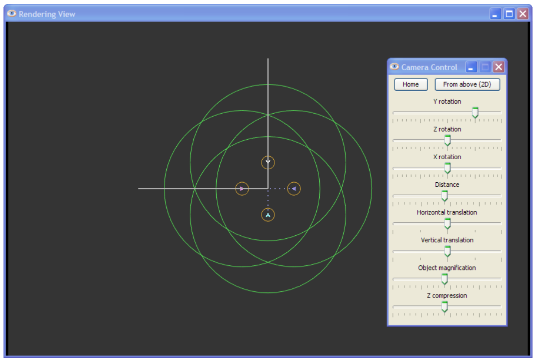


Fig. 3. SMARC Simulation window (2D view)

The program architecture allows for different algorithm to be implemented and tested side-by-side. Some simple statistics, such as the presence of missed separations and the global efficiency (as defined above) are collected and can be displayed and exported. A simulation configuration can be stored on a file and later reloaded and re-rendered.

IV. Current Research

A. Test scenarios

In these preliminary simulation, we still concentrate on the 2D case, deliberately forcing high airplane densities at the same altitude in order to stress the agents by increasing the complexity of interaction between them.

We test the robustness of our algorithm on a very unrealistic and 'pessimistic' scenario: all the flights go trough a choke point at the same time. A predetermined number of aircraft are distributed around a circle with a radius of 50 miles. Each aircraft has its destination at the exact opposite side of the circle, and it will disappear while reaching its destination. This scenarios represents a challenge for any conflict resolution algorithm: as the number of aircraft increase, there is a corresponding increase in the traffic density (because the circle has a fixed radius), and applying SGT we obtain good results both in terms of absence of missed separation and efficiency. No loss of separation occurred for a maximum of 14 aircraft in a circle of 50 nmi radius, i.e. a regime of very high densities.

In Fig.(4) we present 4 snapshots of the choke point scenario for 12 aircraft. As reported in Fig.(5)also in the case of 14 aircraft the Separation Assurance is preserved. We can notice in Fig.(6) that, as density increases the SGT exhibits a graceful degradation with respect to efficiency.

Another test is on a 'perpendicular flows' scenario, where two linear traffic flows intersect at right angles, one moving from left to right and the other moving from top to bottom. In Fig.(7) a sequence of 4 screen snapshot from one simulation run. For this scenario, we use a proximity radius of 100 nmi. As the flows approach the intersection point, the aircraft change their direction to avoid violations of the 5 nmi separation distance. There are no missed separations for an arbitrary large numebr of aircraft (keeping a fixed distance between aircraft of 8 nmi), but increasing the number of aircraft, there

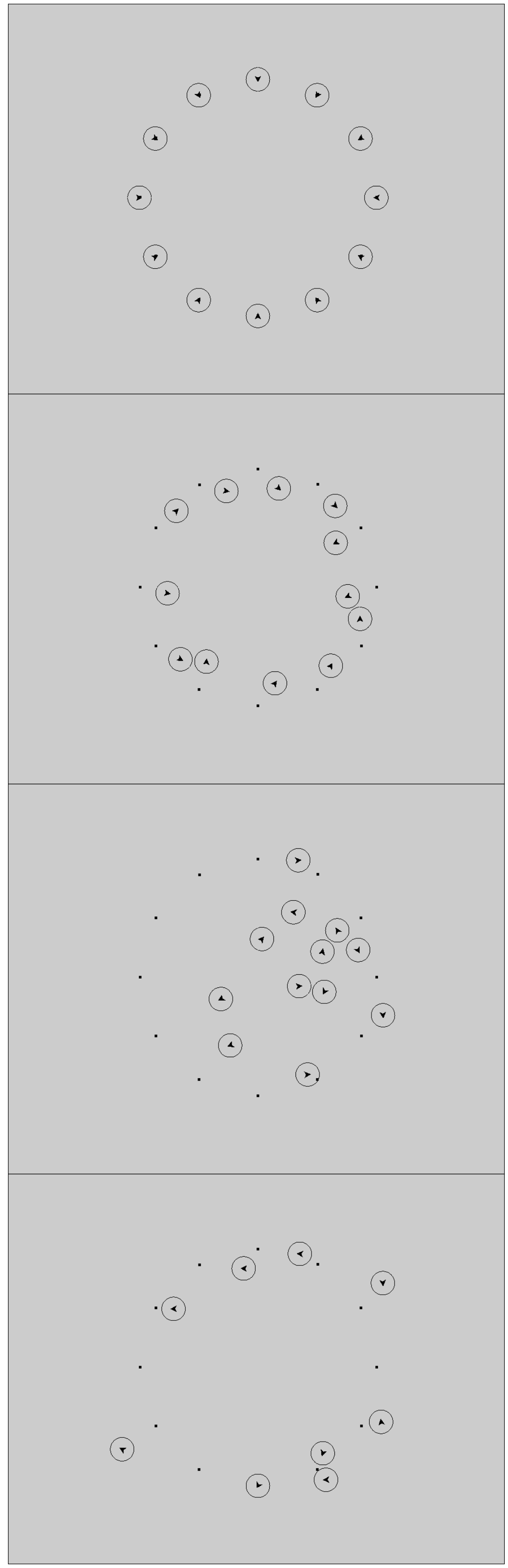
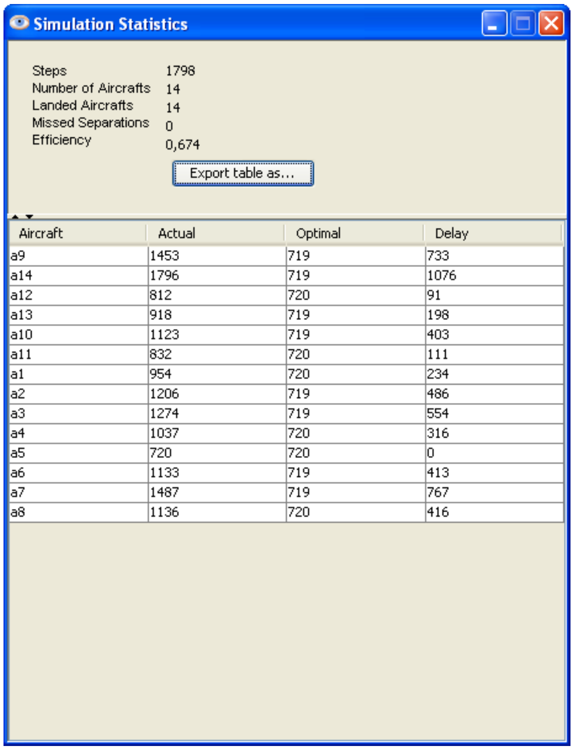


Fig. 4. Snapshots of the choke point scenario with 12 aircraft.



Simulation Statistics

Steps 1798
Number of Aircrafts 14
Landed Aircrafts 14
Missed Separations 0
Efficiency 0,674

Export table as...

Aircraft	Actual	Optimal	Delay
a9	1453	719	733
a14	1796	719	1076
a12	812	720	91
a13	918	719	198
a10	1123	719	403
a11	832	720	111
a1	954	720	234
a2	1206	719	486
a3	1274	719	554
a4	1037	720	316
a5	720	720	0
a6	1133	719	413
a7	1487	719	767
a8	1136	720	416

Fig. 5. Table summarizing statistical results for choke point scenario with 14 aircraft.

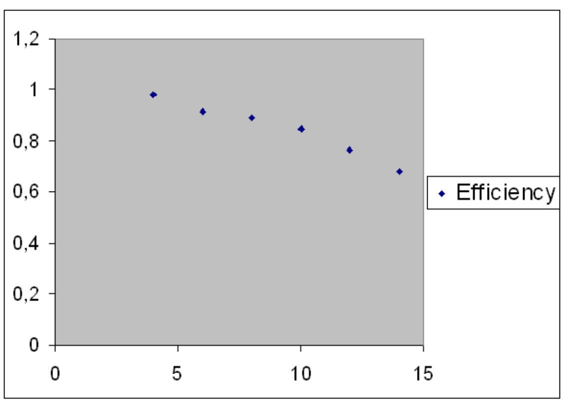


Fig. 6. Efficiency vs. number of aircraft.

is a consequent loss of efficiency. In Fig.(8) we report some results about the frequence of separation violations, efficiency and individual paths and delays for a 'perpendicular flow' scenario with 12 aircraft.

We will address in future research further improvements and tests of our algorithm. First, we are going to evaluate the algorithm using randomly generated traffic with high densities (e.g. more than twice the actual European average density) . Then we will compare performance of our conflict resolution software tool with other tools based on different algorithms , e.g. Hoekstra [13] ,[14] and Krozel [15], in order to identify the strengths and weaknesses of our algorithm.

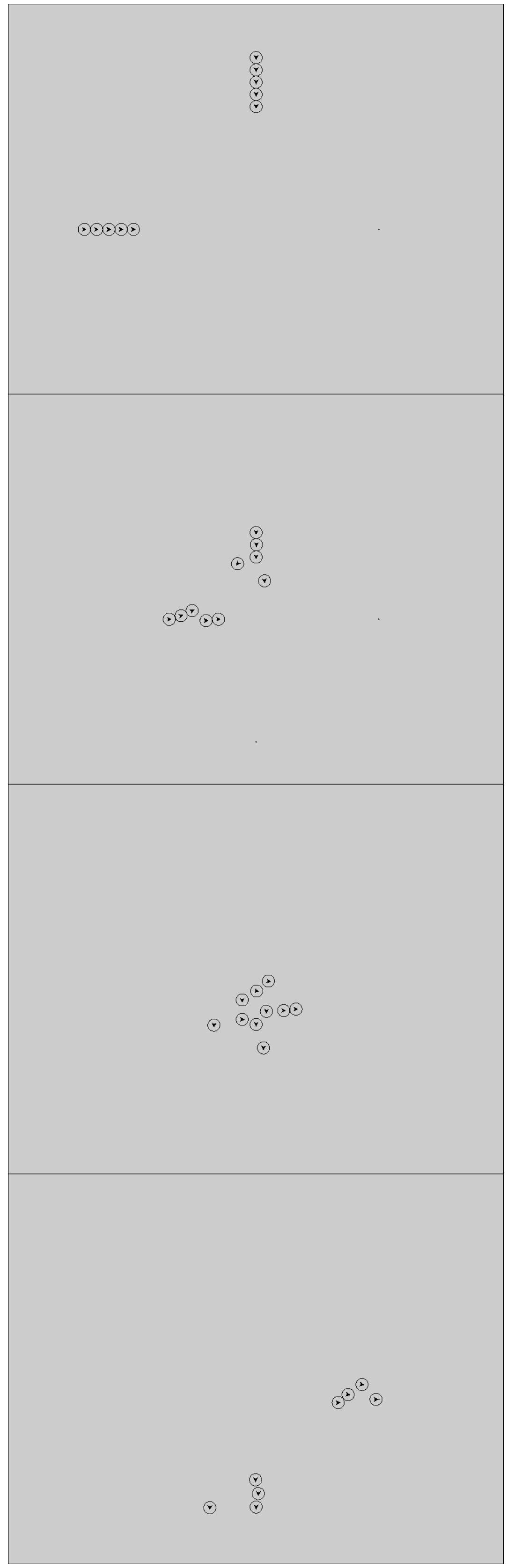
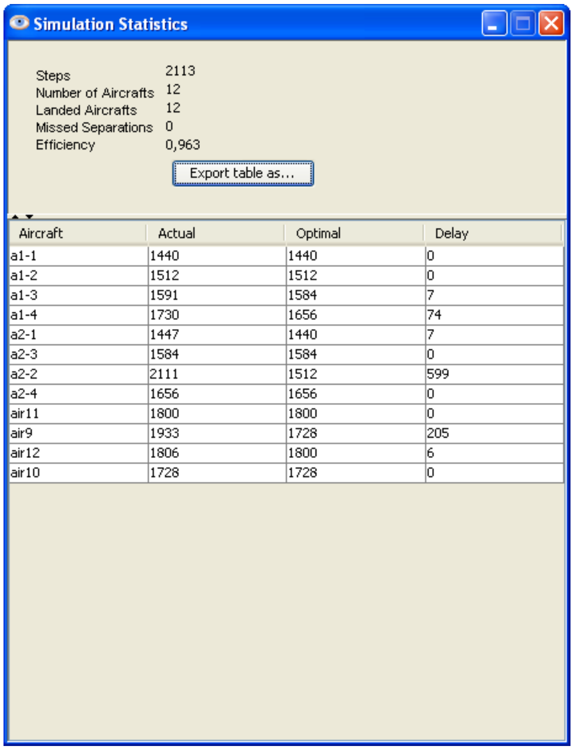


Fig. 7. Snapshots of the perpendicular flows scenario with 10 aircraft.


Simulation Statistics

Steps	2113
Number of Aircrafts	12
Landed Aircrafts	12
Missed Separations	0
Efficiency	0,963

Export table as...

Aircraft	Actual	Optimal	Delay
a1-1	1440	1440	0
a1-2	1512	1512	0
a1-3	1591	1584	7
a1-4	1730	1656	74
a2-1	1447	1440	7
a2-3	1584	1584	0
a2-2	2111	1512	599
a2-4	1656	1656	0
air11	1800	1800	0
air9	1933	1728	205
air12	1806	1800	6
air10	1728	1728	0

Fig. 8. Table summarizing statistical results for the perpendicular flows scenario with 12 aircraft.

TABLE I
EXAMPLE OF INPUT DATA FROM THE FAST TIME SIMULATION.

IDV	*DEP*	*ARR*	*TIP*	*FPL LEV*	*FIX*	*LEV*	*TIME*
*JET*5059	*LOWW*	*LICJ*	*A*320	310	*GIRDA*	310	00.09.07
*EEZ*1717	*LIRF*	*LIPX*	*A*320	310	*TIBER*	127	00.12.19

B. Real traffic dataset

ENAV has already provided access to some realistic traffic flows, in particular data from the Fast Time Simulation of a whole day with a very high traffic density, i.e. 09/07/2006, for the Padova Area Control Center.

The input files are in csv format and they contain, for each flight, the following information: flight ID, airports of departure and arrival, aircraft model, average level during the flight and then all fixed points in aircraft route, with level and time at which the aircraft reached them.

We will use this first set of data provided by ENAV as a baseline to test our algorithm, first concentrating on interesting and typical cases involving a small number of aircraft. Then we will try to manage with our algorithm all the traffic during the whole day, comparing our simulation with ENAV Fast Time Simulation.

In order to test and improve the simulation platform, we plan to get further data on potential conflict situations that have been dealt by human controllers in a Real Time Simulation (i.e. the Real Time Simulation held in Rome for the 'European ATM Validation Platform AMAN Project' in 2004) and compare the results with the solution proposed by our algorithm, with respect to separation assurance, delays and the emergence of different traffic patterns in a Airborne Self-Separation environment.

V. OPEN ISSUES

The introduction of automated conflict resolution tools will lead to new challenges in ATM: there are several open issues, that we will address in future works.

We will analyze the safety implications, both in normal and abnormal conditions (e.g. equipment failures or severe weather conditions). We will take into account the potential hazards that could arise from the use of our on-board decision supporting tool, and identify possible mitigation strategies that could reduce their likelihood, or the severity of their effect. We will also identify the requirements for a decision supporting software in order to meet security and dependability concepts, evaluating how the introduction of highly sophisticated, firmly mathematically grounded conflict resolution techniques can improve robustness, flexibility and real-time adaptation for future ATM in a Airborne Self-Separation context, also in crisis scenarios.

We will inquire technological feasibility of introducing into ATM automation mechanisms, protocols and tools issued from the Satisficing Game Theory approach, with particular attention for the problem of secure and reliable exchange of information between aircraft.

We will also focus on the integration and interaction with the existing tools.

Technical implementation of new algorithms is only one component of the introduction of automation into ATM, and human factor and organizational issues need to be addressed since the very early stages of the development of new technologies. Thus, we will make use of controllers and pilots' expertise to realistically evaluate the impact of such tools on their work, assessing to which extent and how it will affect their everyday activity.

Moreover, we will start analyzing the expected impact of redefinition of roles, procedures, ATM instruments and tools, focusing on the transition phase between two different operational concepts.

VI. CONCLUSION

As traffic densities increase, the need for new algorithms that automate decision making will continue to grow. The Satisficing approach is well mathematically grounded and provides a natural mechanism for cooperation that optimises the overall traffic trajectories, while ensuring the minimization of risks. Our preliminary simulation experiments confirm the flexibility and the good performance offered by Satisficing Game Theory in a Airborne Self-Separation environment. We are exploring new extension of the algorithm, that will take in account more realistic conditions, and we will compare our simulation results with real cases handled by controllers.

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Research of the Relation between the Hourly Inbound Capacity at Schiphol Airport and the Number of KLM Transfer Passengers at Risk of Loosing their Connection

Dragana Mijatovic, Marleen Meert, Khalid El-Bachraoui, Javier Wanga

***Abstract*— KLM provides connections to almost 8 million arriving transfer passengers per year at one of the major airline hubs in Europe – Amsterdam Schiphol airport. To provide reliable connections, it is of great importance that KLM's flights have a high arrival punctuality. Therefore, it is essential to understand all factors that influence arrival punctuality and to relate those factors to the reliability of KLM's connections at Schiphol airport.**

In this paper all factors which affect the arrival punctuality of KLM flights into Schiphol airport are identified and their significance is determined. The contribution of ATC the Netherlands (the Dutch Air Navigation Service Provider (LVNL)) ranges from about 8-15% for the KLM flights that arrive late according to the timetable. A significant portion of delays, however, is a consequence of a combination of the LVNL and other factors which cannot be distinguished further.

It has been found that the contribution to non-punctuality is about 5% higher for arrivals in winter. This effect can be attributed to the increased number of the ATFCM (Air Traffic Flow and Capacity Management) restrictions due to weather conditions.

The relation between the arrival punctuality and the percentage of passengers at risk of loosing their connecting flights has been studied. It appears that the increase in the arrival punctuality ensures lower percentage of passengers at risk of loosing their connection. Finally, the critical capacity at Schiphol is determined. When the capacity – demand ratio drops below the critical value a significant increase in the percentage of passengers at risk of loosing their connection will occur.

***Index Terms*—ATC the Netherlands, inbound capacity, KLM, Schiphol airport, transfer passengers**

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I. Introduction

As a result of KLM's growth strategy in the 1980s and 1990s, Schiphol airport has become one of the major airline hubs in Europe. KLM has about 11 million passengers each year arriving at Schiphol of which 70% are transfer passengers. To serve these transfer passengers, KLM must assure high quality connections at the Schiphol hub, providing a quick but reliable connection onto the next flight. To offer an attractive travel schedule to its passengers KLM designed its timetable to minimize the travel time between origin and destination through short connection times.

In order to maximize the number of high quality connections at Schiphol airport, KLM's timetable has been constructed into several arrival and departure waves or banks (see Fig. 1). The duration between scheduled arrival time and scheduled departure time of a connection should be at least the minimum connecting time (MCT). If it is shorter than the MCT, passengers cannot make a connecting flight and tickets for such connections cannot be sold.

As air travel demand increases, KLM faces the challenge to optimize and expand its hub operation at Schiphol airport as part of the competition between global airline alliances. To maintain and expand its market share KLM must offer more attractive connections through its hub at Schiphol. This growth of connectivity requires an increased number of flights in arrival and departure banks. This increased peak demand leads to saturation of airport capacity at the expense of increased arrival-delays, which in turn affects the reliability of connections which is vital to KLM's operation.

The development of KLM's network thus is determined by the balance between airport capacity and network demand. This capacity – demand balance governs both KLM's strategic[1] and tactical[2] decision making process. To optimize this decision making process it is necessary to understand all factors which play a role in KLM's key performance indicators such as arrival punctuality (see Table I) as well as

[1] *Strategic: referring to KLM's network development process.*

[2] *Tactical: referring to the network management process on the day of operation.*

to couple them to the percentage of transfer passengers at risk of loosing their connections.

This paper qualitatively presents the shares of factors that contribute to non-punctuality of arriving flights. The critical value of the inbound capacity has been determined. When the capacity drops below the critical value, the number of passengers at risk of loosing their connection significantly increases. The relationships established in the study lay the basis for decision support models and tools which can help KLM in developing and optimizing its network operation at Schiphol airport.

II. Definitions

A generic flight sequence consists of several phases: ground handling at the feeder airport, taxiing, airborne phase, taxiing and ground handling at the hub airport. During each process, a delay can occur due to several reasons. Therefore, in the majority of the flights on a certain route, the expected delay will be included into the scheduled flight time. This is a costly measure but necessary to assure punctuality and therefore the passenger connectivity.

Table I gives a list of the definitions used in this paper.

III. Approach

In order to research the relation of the hourly inbound capacity and the number of KLM transfer passenger who are at risk of loosing their connection (sub-MCT passengers), the approach that has been used is illustrated in Fig. 2. The arrival punctuality according to the KLM time table is central. It is influenced by a number of the LVNL- and non-LVNL - factors on one hand and it is related to the percentage of the sub-MCT passengers on the other hand.

It is proceeded in the following way:

- all factors in the LVNL- and non-LVNL- contribution to arrival punctuality that are relevant for this project are identified;
- the percentages of the LVNL- and non-LVNL-contribution to arrival punctuality are determined;
- the following empirical relations were researched between:
    - the hourly inbound capacity (as one of the LVNL- contributions) and the arrival punctuality. Relations between the non-LVNL- contribution and the arrival punctuality are outside the scope of the project;
    - the arrival punctuality and the percentage of the sub-MCT passengers;

the hourly inbound capacity and the percentage of the sub-MCT passengers.

It should be noted that in this research the percentage of the sub-MCT passengers used differs from the actual percentage of passengers who cannot make their connections. Although a number of passengers arrive with the effective transfer time smaller than the MCT, in some cases it is still possible to make their connections (such as: gates are close to each other, departing flight was delayed, passenger can reach the gate faster than assumed in the MCT value etc.). Therefore, the actual percentage of passengers who cannot make their connection is lower than the percentage of the sub-MCT passengers. The percentage of the sub-MCT passengers is used here instead of the actual percentage of passengers who cannot make their connection to avoid a number of effects at the airport that cannot be influenced by the LVNL (such as: delays of the departing flights, delays in opening the aircraft doors etc.). Actual number of passengers who miss their connection is a result of a daily (tactical) handling of flights. It is not suitable for our research, because the results of the research will be used for the strategic development at Schiphol.

IV. Methods and Results

A. *LVNL- and non-LVNL-contributions to arrival punctuality*

The LVNL- and non-LVNL- contributions to arrival punctuality were identified and listed in Fig. 2.

The order of magnitude of the LVNL- and non-LVNL-contributions to arrival punctuality has been determined to be able to estimate their influence on arrival punctuality. To determine the percentages of the LVNL- and non-LVNL-contributions the definitions of FIR-delay and arrival delay (see Fig. 3 and Table I) and the algorithm from Fig. 4 have been used.

It is determined for each flight if it departed on time from the feeder airport (see Fig. 4). If not, it is researched what the reason was for the late departure:

- delays caused by aircraft handling or “snowballing” effect or
- en-route restrictions and/or restrictions at the departure airport or
- reduced LVNL capacity

For all flights FIR- and arrival delay is calculated and each flight is placed in one of the following categories - flight with:

a) Arrival delay due to the LVNL-contribution (marked with blue);
b) Arrival delay due to non-LVNL-contribution (marked with yellow);
c) Arrival delay due to the combined LVNL- and non-LVNL-contribution (marked with green);
d) Non-delayed arrival (marked with orange). This category can be subdivided into different categories (as given in Fig. 4).

To convert the above-described schematics into the percentages, the percentages of each contribution were determined as in Fig. 4. The percentage of the LVNL-contribution is calculated as a number of flights which fulfil the conditions given by the blue rectangles (Fig. 4) and divided by total number of flights. It is marked with A. The same approach was used for other contributions. It can be concluded that the boundary conditions of the LVNL-contribution-value is between the A- and (A+C)- value (Fig. 4).

Fig. 5 shows the values of the LVNL-, non-LVNL- and combined (LVNL- and non-LVNL-) contributions only of the delayed flights for the months August 2005 and 2006 and December 2005 and 2006. It can be concluded that pure LVNL- contribution of the delayed flights is under 10% in the summer months and it is around 15% in the winter. Increase of the LVNL- contributions in the winter can be attributed to the fact that in the winter the capacity at Schiphol is more often reduced due to the bad weather conditions. KLM works with 7 banks system from summer 2006 (see Fig. 1) and in 2005 it worked with 6 banks system, but no significant difference in the LVNL- contributions for the same months in both banks systems can be observed.

In general it could be said that the pure non-LVNL-contributions are in the range of 20% until about 40% and they do not seem to be season dependant. This can be explained by the fact that only a small part of an inbound flight is managed by the LVNL and delays experienced outside the Dutch FIR can be of different nature and therefore irregularly spread throughout the year. Since the margin of the LVNL-contributions could be from the value A until A+C (see Fig. 4), the calculation shows a broad range of the LVNL-contribution: 8% until 80% for all delayed flights, because there are a number of situations when it is not possible to distinguish between the LVNL- and non-LVNL-contributions.

B. Relations between the hourly inbound capacity, arrival punctuality and percentage of the sub-MCT passengers

Further the research is focused on finding the relations between the hourly inbound capacity (as one of the LVNL-contributions to arrival punctuality), arrival punctuality and the percentage of the sub-MCT passengers (Fig. 6). Hourly inbound capacity consists of the capacity forecast and delta capacity (see Table I).

The relations found are illustrated in Fig. 7. They are given for the first busy bank of the day (see Fig. 7(a)) for summer 2006 and winter 2006/2007 in the periods when two landing runways were in use and one runway was used for the departures (from about 7.30 until 9.15 LT). This bank is chosen as an example, because demand of the flights in the core of the bank is close to the maximum inbound capacity. Moreover, this bank does not suffer from the snowballing effect as could be the case in the other banks that follow.

In Fig. 7(a) the arrival punctuality vs. delta capacity is shown. This graph shows a very scattered pattern which means there are many other factors than LVNL ones influencing the arrival punctuality. It does show that if demand is lower than the capacity the probability is higher that the arrival punctuality will be high as well.

Graph in Fig. 7(b) presents the percentage of the sub-MCT passengers vs. arrival punctuality. As expected, higher arrival punctuality results in low percentage of the sub-MCT passengers.

The experts' experience shows that during the peak periods more delays occur when demand at the airport is close to available capacity. Graph in Fig. 7(c) presents delta capacity vs. capacity forecast for the first busy bank of the day. From this graph the capacity demand (capacity forecast value when the demand is equal to the capacity forecast) is determined and it is the same in both seasons. Additionally, critical capacity and corresponding critical delta capacity for each season are denoted, because between the capacity demand and critical capacity, the percentage of the sub-MCT passengers (as it will be discussed below) will not change significantly.

Graph in Fig. 7(d) shows the percentage of the sub-MCT passengers vs. capacity forecast. It can be observed that when the capacity forecast is above the capacity demand value the percentage of the sub-MCT passengers is low and it does not vary much. This stands also in case the capacity forecast has a value between the critical capacity and capacity demand values (i.e., within the capacity margin, (see Fig. 7(d)), whereas below the critical capacity the percentage of the sub-MCT passengers significantly increases. The trend lines are not given, because below the critical capacity value there is not enough data to obtain the reliable fits.

Graph in Fig. 7(e) shows the percentage of the sub-MCT passengers vs. delta capacity. The percentage of the sub-MCT passengers is low and shows no significant spread when the capacity at Schiphol is not put under pressure (delta capacity is positive). The percentage of the sub-MCT passengers has similar behaviour even when the demand is slightly higher than the capacity forecast, i.e., between the zero value of the delta capacity and the critical delta capacity (on the graph the critical delta capacity for summer and winter seasons are denoted). Below the critical delta capacity, the percentage of the sub-MCT passengers increases (Fig. 7(e)). Due to the large spread in the percentage of the sub-MCT passengers when the delta capacity is below the critical delta capacity value, the trend line is not given and more data is needed for the reliable fits.

It can be concluded that hourly inbound capacity is related to the percentage of the sub-MCT passengers (see Fig. 6, Fig. 7(d), (e)), because of the strong relation between the arrival punctuality and the percentage of the sub-MCT passengers (Fig. 7(b)) despite the weak relation between the arrival punctuality and delta capacity (Fig. 7(a)).

V. Conclusion and Outlook

It is important for the development of KLM's network to understand all factors, which play a role in KLM's key performance indicators, such as arrival punctuality of the inbound flights to Schiphol. Arrival punctuality and subsequently the percentage of the sub-MCT passengers of a flight arriving at Schiphol are influenced within the Dutch FIR by the LVNL and non-LVNL- contributions. In this paper all

LVNL- and non-LVNL- contributions to arrival punctuality of the KLM flights with transfer passengers on board are listed. It can be concluded that pure LVNL- contribution in case of the delayed KLM flights is under 10% in summer months and it is increased for about 5% in winter months. This can be mainly attributed to bad weather conditions in winter, when number of the ATFCM restrictions at Schiphol is increased.

Further, the relations between the hourly inbound capacity (as one of the LVNL- contributions), arrival punctuality and the percentage of the sub-MCT passengers are researched. Using these relations a critical capacity was determined, above which the percentage of the sub-MCT passengers is low and it does not vary much with the change in the capacity. Below the critical value the percentage of the sub-MCT passengers increases more rapidly.

Finally, the relation between the percentage of the sub-MCT passengers and arrival punctuality confirms the intuitive expectations that the increase in the arrival punctuality reduces the percentage of the sub-MCT passengers.

These results will be used in the follow up research to find an empirical relation between the sustainability of hourly capacity[3] at Schiphol and percentage of the sub-MCT passengers as well as a relationship between the sustainability and the arrival punctuality. If it would be possible to establish these relations, they would be used to estimate the changes in the percentage of the sub-MCT passengers and/or in the arrival punctuality if the sustainability of hourly capacity and/or declared capacity at Schiphol would change. This can give an indication of the changes in reliability of connections offered.

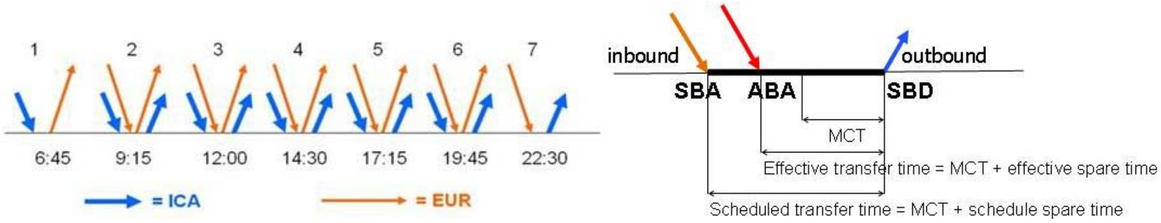
ACKNOWLEDGMENT

This paper presents a part of results of a project "Research of the relation between the KLM No Connection (NOC)-rate and sustainability of hourly capacity at Schiphol airport" conducted by the Knowledge and Development Centre Mainport Schiphol (KDC). The authors would like to thank the project team members: L. Hoogerbrugge (LVNL), J. Goedhart (KLM), B. Gimberg (AAS), A. Geebelen (AAS), H. Erens (LVNL), R. Frijns (KLM), R. Rooij (KLM), W. van Miltenburg (KLM), the steering group members: B. van der Weyden (KLM), J. Kerckhoff (KLM), S. Lentze (LVNL), P. Cornelisse (KLM) as well as Y. de Haan (KLM), E. Westerveld (LVNL), T. Dortmans (KLM), L. Oudkerk (KLM), Y. Obbens (LVNL), F. Dijkstra (LVNL), F. Bloem (LVNL) and G. Gardner (TU Delft) for the valuable discussions.

LIST OF ABBREVIATIONS

AAS	Amsterdam Airport Schiphol
ACC	Area Control Centre
ATC	Air Traffic Control
ATFCM	Air Traffic Flow and Capacity Management
FIR	Flight Information Region
KLM	Royal Dutch Airlines
LT	Local Time
LVNL	Luchtverkeersleiding Nederland (Air Traffic Control the Netherlands)
MCT	Minimum Connecting Time

[3] *Sustainability is a percentage of time a declared capacity is indeed realized by the providers.*



(a) (b)

Fig. 1. (a) Inbound and outbound KLM flights are organized at present in 7-banks system at Schiphol. Times shown are the local times (LT). Intercontinental flights (ICA) are denoted with the blue lines and European flights (EUR) with the orange ones; (b) Schematic representation of connecting flights: orange arrow represents the inbound flight (SBA-scheduled on-block arrival, i.e., the time a flight is scheduled to arrive at the gate, according to the timetable); red arrow: delayed arrival (ABA-actual on-block arrival; i.e., the time the flight actually arrived at the gate); blue arrow-outbound flight (SBD-scheduled off-block departure; i.e., the time a flight is scheduled to depart from the gate, according to the timetable). Scheduled transfer time is the time between the scheduled on-block arrival of the inbound flight and scheduled off-block departure of the outbound flight the passenger is transferring to (calculated as SBD-SBA). Scheduled transfer time consists of the MCT and the scheduled spare time. Effective transfer time is the time between actual arrival time (gate) of the inbound flight and the scheduled departure time (gate) of the outbound flight the passenger is transferring to (calculated as SBD-ABA). Effective transfer time consists of the MCT and effective spare time.

TABLE I
LIST OF DEFINITIONS USED IN PAPER

	Definitions
Arrival punctuality	The percentage of flights that arrived on time or earlier compared to the scheduled arrival time, i.e., SBA (at the gate).
Arrival delay	The difference in time between scheduled on-block arrival time (at the gate) according to the timetable (SBA) and the actual on-block arrival time (ABA), i.e., ABA-SBA. A flight that arrived earlier than or at the SBA is considered to be “on time”. One minute late or more is considered to be “delayed”.
FIR delay	A delay of a flight within the Dutch Flight Information Region (FIR). It is calculated as a difference between the actual time an aircraft flies[a] and taxies from FIR boundary until gate (ABA-FIR) and a sum of nominal flight and taxi times from FIR entry through specific sector to specific runway and from there to gate.
Transfer passenger	A passenger with the ticket for the connecting flight, arriving at Schiphol on a KLM inbound flight and leaving Schiphol on an outbound flight of any carrier.
Minimum connecting time (MCT)	A minimum transfer time between the inbound and outbound flights a passenger[b] needs to make a connection to. Tickets can be sold only for the connecting flights with scheduled transfer time of at least MCT. For Schiphol, the MCT between both European inbound and outbound flight is 40 minutes, other connections have MCT of 50 minutes.
Sub-MCT passenger	A transfer passenger having an effective transfer time of less than MCT.[c]
Capacity forecast	A number of landings per hour, which can be realized based on the expected availability of the runways (due to the weather conditions, maintenance of the runways and/or available staff)). It is issued 4 times a day for the next 6 hours by LVNL (ATC the Netherlands).[d]
Demand	A number of planned landings (of all airlines) on Schiphol filed a day before their actual landing.[e]
Delta capacity	A difference between the capacity forecast and demand.

[a] *Actual flight time can be extended significantly due to the tactical flight management (see Fig. 2): vectoring (stretching the flight path) and/or use of holdings.*

[b] *It is assumed that the baggage of the passengers is transferred together with the passenger to the connecting flight.*

[c] *In this paper it is assumed that departure flights depart on time.*

[d] *It may differ from the actual capacity, but rarely and therefore gives a reliable indication of the capacity at Schiphol.*

[e] *Data are received from the Amsterdam Airport Schiphol (AAS) and KLM.*

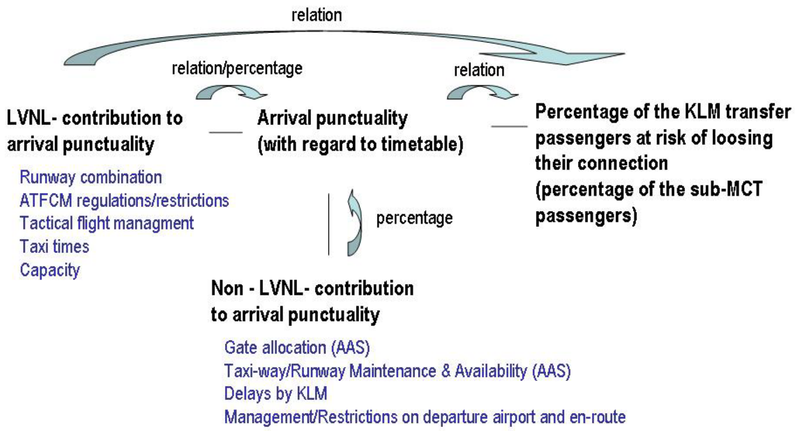


Fig. 2. Schematic representation of the project approach. Arrival punctuality is central. The LVNL- and non-LVNL-contributions to arrival punctuality relevant for this project are determined (the list is given below each contribution).

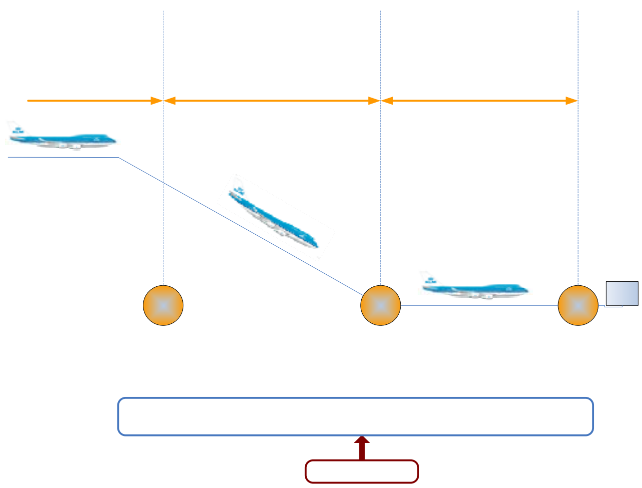
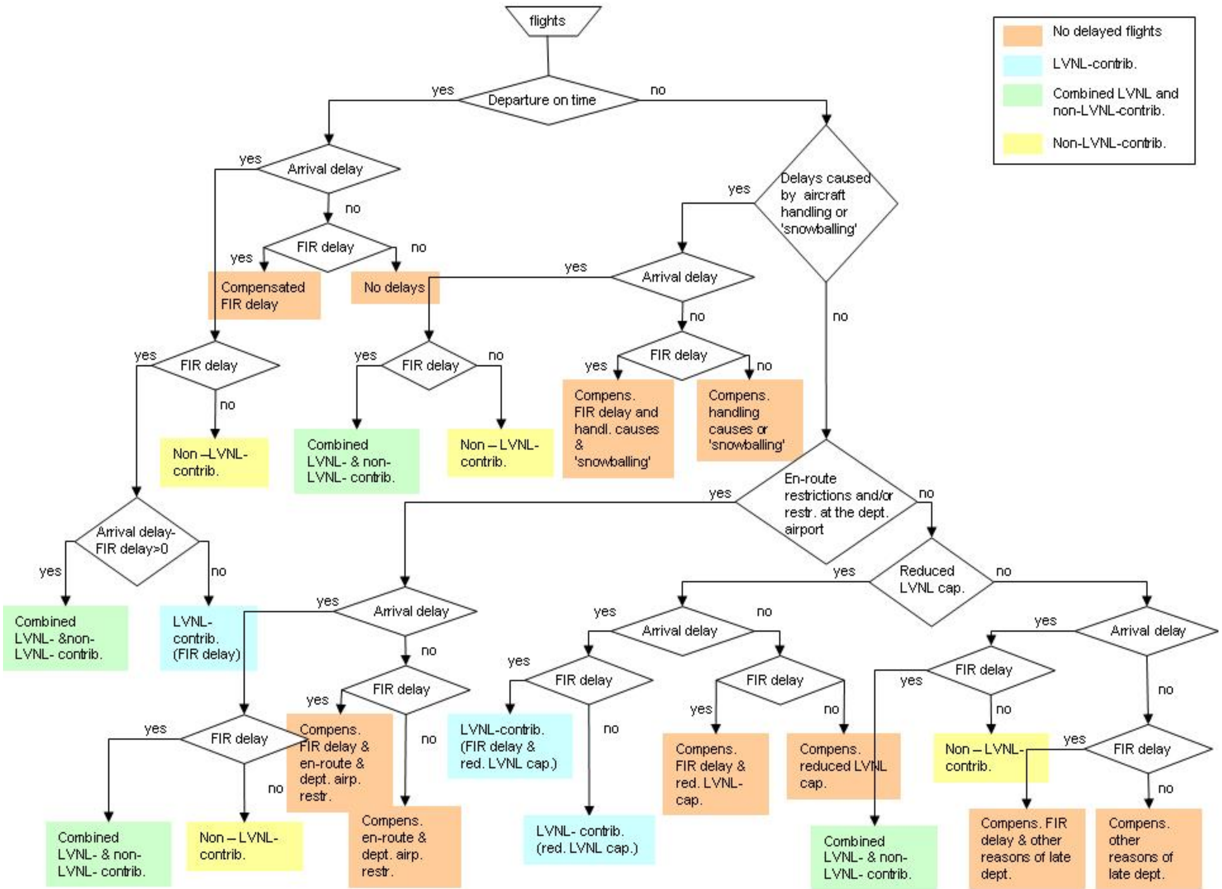


Fig. 3. Definitions needed to determine the LVNL- and other contributions. FIR stands for the time an aircraft arrived at FIR boundary, TDT is a touch-down time[a], ABA is Actual on-Block Arrival and SBA is scheduled on-block time of arrival (according to the timetable). Nominal flight times[b] are determined from the data from the LVNL and KLM. Nominal taxi times[c] are determined from the data measured by LVNL.

[a] *Touch down time (TDT) is taken from data from the LVNL. It is measured as a time an aircraft crosses the runway threshold. It is assumed in this project that the plane actually landed on the threshold, although this does not have to be the case. Since the touch down time cannot be more precisely determined, this value is used as the TDT.*

[b] *Nominal flight time is calculated as a median value of the difference between the touch down time (TDT) and time of the FIR entry (FIR): Nominal flight time =* $(TDT\text{-}FIR)_{median}$*. It is calculated for an undisturbed flight from each ACC sector entry until a particular runway.*

[c] *Nominal taxi time is calculated as a difference of the time the aircraft crosses the red line (the border between the platform and manoeuvring area - it is considered in that case that the aircraft reached the gate) and the touch down time: Nominal taxi time = (time (crossing the red line) - TDT))*$_{aver}$*. Only average taxi times are available at LVNL.*



A $$\textbf{LVNL-contribution (\%)} = \frac{\text{Number of flights fulfilling conditions}}{\text{Total number of flights}} \times 100$$

B $$\textbf{Non-LVNL-contribution (\%)} = \frac{\text{Number of flights fulfilling cond.}}{\text{Total number of flights}} \times 100$$

C $$\textbf{Combined LVNL \& non-LVNL-contr. (\%)} = \frac{\text{No. fl. fulfil. cond.}}{\text{Total number of flights}} \times 100$$

D $$\textbf{Total non-delayed flights (\%)} = \frac{\text{No. fl. fulfil. cond.}}{\text{Total number of flights}} \times 100$$

$$\boxed{A \le \text{LVNL-contribution} \le A + C}$$

Fig. 4. Algorithm used to determine the percentage of the LVNL- and non-LVNL- contributions to arrival punctuality and equations used to determine these percentages. Delay codes from KLM were used to specify the causes of the delayed departures from the departure airport. Delay codes are given by KLM to each delayed flight and they are associated with the reasons of the delays.

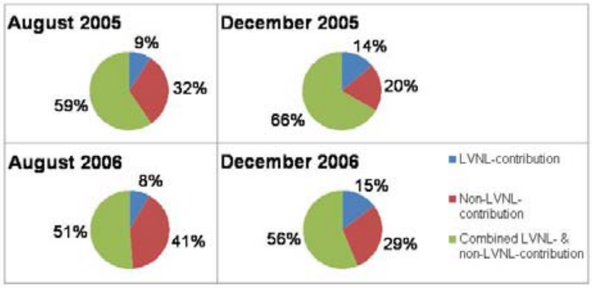


Fig. 5. Pies show the LVNL-, non-LVNL-, and combined LVNL- and non-LVNL- contributions for months August and December 2005 and 2006. Combined contributions are rather large since there are a number of situations when it is not possible to distinguish between each contribution. For example, the flight is delayed 30 minutes according to the time table and it had a FIR- delay of 10 minutes. This means that the rest 20 minutes of the delay is a consequence of the non-LVNL- contribution, for instance, en-route delay.

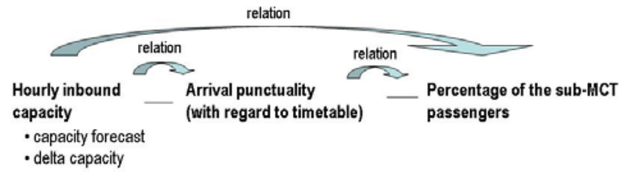


Fig. 6. Relations which are researched and presented further. Hourly inbound capacity is one of the types of capacity mentioned in Fig. 2 as a general term.

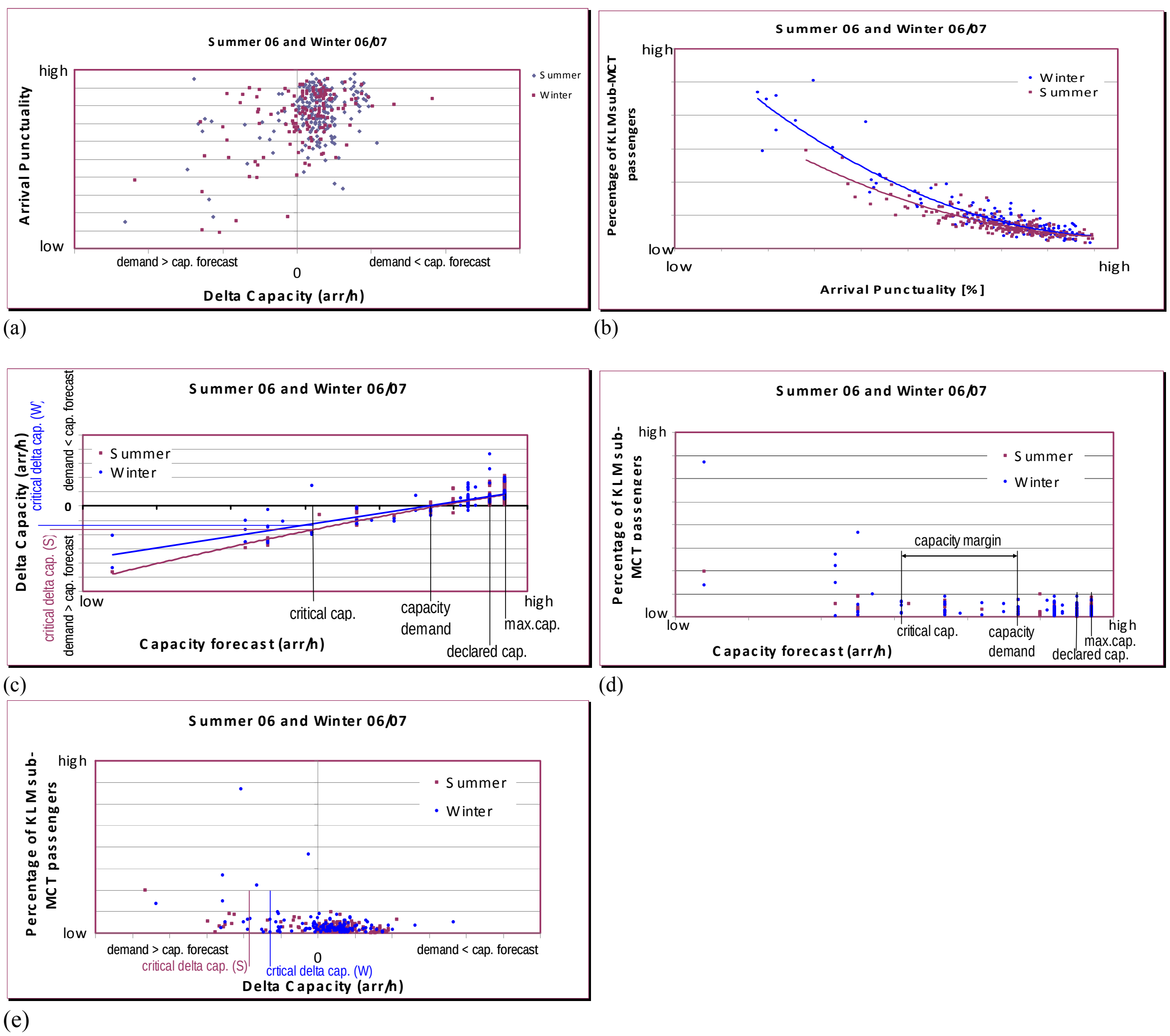


Fig. 7 Relations found for the first busy bank of the day when 2 landing runways were in use for the seasons summer 2006 and winter 2006/2007. The exact values on the axis are not given, because of commercial sensitivity of data for the parties involved in the research. (a) Arrival punctuality vs. delta capacity; (b) Percentage of the KLM sub-MCT passengers vs. arrival punctuality; (c) Delta capacity vs. LVNL capacity forecast. Capacity demand is defined as a capacity when the demand reaches the capacity forecast value. Declared capacity is a number of landings per hour that can be handled by the LVNL. It is determined for a longer period of time (year) and slot allocations are based on it. Declared capacity is 68 landings per hour for years 2006 and 2007. Sometimes more landings can be realized and the maximum capacity is thus higher than the declared one. Critical capacity is determined from Fig. 7(d) as a capacity above which no significant change in the percentage of the sub-MCT passengers appear. Using this value, critical delta capacity for summer and winter were determined from the fits; (d) Percentage of the KLM sub-MCT passengers vs. LVNL capacity forecast; (e) Percentage of the KLM sub-MCT passengers vs. delta capacity.

TIMELINE FLIGHT PLAN DATA: a Way to Improve Controllers' Mental Representation

Jean Yves GRAU and Horst HERING

Abstract— **TimeLine is an exploratory way for presenting flight plan data in which beacons are chronologically positioned on a timeline. They are positioned according to their estimated over-fly times which are determined from radar data. This way of displaying data gives an isomorphic representation of the distance travelled as a time reference. It supports Air Traffic Control Operators' (ATCO) understanding of the air traffic and identifies conflicts between aircraft. A first experiment in 2003 with a static paper version of the TimeLine concept showed the interest of the concept. Following this the EUROCONTROL Experimental Centre developed an electronic TimeLine demonstrator. This demonstrator was used to evaluate the TimeLine. The experiments are described in this paper. Sixteen ATCOs carried out two air traffic control scenarios, one with the traditional presentation of flight plan data, the other with the TimeLine. The results confirm the advantages of the TimeLine presentation in improving the ATCOs' traffic mental representation and increasing the level of safety and performance.**

***Index Terms*—Air Traffic Controller, Conflict detection, Flight plan data, Mental representation, Safety.**

I. INTRODUCTION

ATM R&D is going towards new operational concepts in order to face with the traffic growth, and in which the Air Traffic Controllers' tasks will change. Automation is considered as a promising way to meet the goals of performance, safety and environment. However, it is now clearly established a full automation cannot be a solution, at least for the next 2 or 3 decades, because the operational environment is full with uncertainties. So human controllers must remain in the decision making loop, and the future ATM system must be human-centred (SESAR, 2006). Keeping high levels of safety requires the Air Traffic Controllers (ATCOs) have the right traffic picture.

Traffic information given to the controllers comes from the radar and the aircraft's flight plans. Radar information allows for managing the traffic in a short-term time horizon while the flight plan data allow for managing in the medium and long-term time horizons. The controller's traffic picture, built from the two information sources, guarantees efficient and safe air traffic control.

Presenting en-route flight plan data to ATCOs is not a trivial matter. ATCO has no direct access to the physical environment of the process being controlled. The mental representation which helps the ATCO understand the situation and make the right decisions suited to proper air traffic management results from what is presented, as well as how it is presented. To increase safety and meet the challenge of increasingly dense air traffic, the mental representation developed by ATCOs must be as operative as possible.

Today, the time-related information involved in flight plans is presented by beacon, whatever output medium is used. The assumption made in the experiments conducted at EUROCONTROL Experimental Centre (EEC) is that presenting flight plan data according to a time-line could make analyzing and understanding air traffic easier.

The concept of a time-line approach was developed by Nobel and Sperandio in the early 70's [1]. This concept is now reaching its full potential, because developments in computerization can provide high-performance interactive instruments. The "time-line" concept involves the following: presentation of flight plan route beacons and estimates according to a dynamic time-line, regularly updated by radar data.

A first experimentation was achieved in 2003 at EEC in the frame of a static simulation where traditional and TimeLine flight plan data were presented on paper strips [2]. The results, elaborated from the comparison between the two modes, about the ATCOs' conflicts detection, shown:

Despite there is no significant difference in favour of one or the other presentation mode regarding the performance and safety, there is a tendency towards less errors with TimeLine. This means nothing argues against TimeLine mode despite the low familiarity and experience level ATCOs have with it regarding the experience they have with traditional mode (several years of practice)

Strip board analysis times are longer with TimeLine while the number of errors is smaller even if the correlation is not significant.

TimeLine presents a greater advantage, notably when new aircraft have to be integrated and for detecting over speeding conflicts.

ATCOs feel TimeLine mode make easier their job by increasing the development of their traffic mental representation. The comfort and confidence feeling they have in their traffic picture was higher, giving them a better control over the task.

However, these promising results might be confirmed by a dynamic simulation in a complex environment of ATC. The purpose of this paper is to present the results of this dynamic experiment led at EEC in 2007.

The paper has four parts: first, an overview of the consequences of different information presentation modes on the development of ATCOs' mental representations; secondly, the description of TimeLine flight plans; then the experiment with its goals and description; and finally, experimental results with discussion.

II. Traditional and Time-Line Presentation Modes

The concept of mental representation comes from the work of Ochanine on operative images [3], Leplat on functional representations [4] and Johnson-laird on mental models [5]. Building a mental representation is understanding [6]. But understanding in a working environment is finalized by the task's goals. This means that beyond what is involved in a working situation, understanding is there to help plan and guide actions as the work situation changes. Mental representations are subjected to constraints coming from the situation, and therefore can differ from one operator to the other because they depend on operator knowledge and experience. Only the most salient dimensions of the situation will be retained, with the operators referring to more or less simple or familiar representations. However, as underlined by Denis & deVega [7], understanding does not necessarily require an entirely analogue model of the situation; an abstract and simplifying representation may be sufficient, depending on the operator's goal.

In this construction of mental representations, information given to operators has a direct impact on mental representations, according to quantity, nature, accuracy and presentation of these data. In Air Traffic Control, Bisseret [8] demonstrated that ATCOs perform two types of operations to develop their own mental representation of air traffic, depending on the information medium on offer:

Logical and mathematical operations for alphanumerical symbolic information, like the ones presented on current's traditional strips (whatever the form the information is displayed: paper or electronic), and

Perception operations associated to analogue interfaces like the radar.

Both information systems have their pros and cons:

The logical and mathematical system is based on applying time- and cognition- consuming algorithms, which involve no uncertainty except for the validity of input information. However the safety margins required (separation criteria between aircraft) to perform logical and mathematical operations are significant and hardly compatible with the increase in air traffic.

The perception system calls on a coding closer to operators' mental representations. But, unlike the logical and mathematical system, perception operations are "fuzzy" and "risky", because they require the ATCO managing his own personal uncertainty. On the other hand, input information is more accurate, and therefore smaller separation standards can be applied between planes.

In practice, both systems complement each other in most existing ATC situations. They explain why the performance and safety levels obtained in ATC are so high. However, they seem stretched to the limit and unable to safely meet the challenge of further increasing air traffic.

TimeLine presents flight plan data and predictions in an analogical fashion.. The TimeLine choice results from the cognitive constraints ATC is based on, notably regarding anticipation and planning. Time deadlines are the essential markers used in ATC, because they can identify future events to prevent hazardous situations and to prepare for favourable traffic flow conditions [9]. The assumption backing the representation of traffic flows on a TimeLine is that this will help ATCOs easily develop more relevant mental representations of the air traffic picture. This approach provides the operator with a cognitive aid, where information is pre-processed so that it arrives in a form which is directly compatible with the ATCO's mental representation [10], and facilitates uncertainty and risk management [11]. TimeLine's strong point is that it introduces flight plan data as a symbolic representation, in an analogical mode of representation differing from the one used with Radars to extrapolate changes over time.

III. Description of Time-Lin Flight Plan

A. *Traditional and TimeLine flight plans*

Traditional flight plan data, still used today in ATC centres include several data shared out among different boxes (fig 1):

The aircraft's call-sign, the Secondary Surveillance Radar Code (SSR), flight plan speed, aircraft type, departure and destination airports, etc.

A series of boxes available for all flight levels (Aircraft Flight Level, Cleared Flight Level, Exit Flight Level, etc.),

A series of boxes used to visualize the aircraft's route, illustrated by a series of beacons printed one after the other, with estimated over fly time.

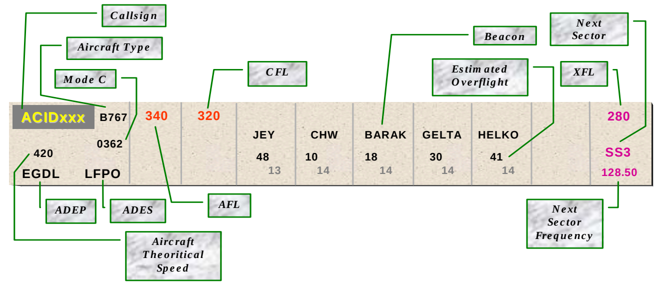


Fig 1. Traditional presentation of flight plan data

TimeLine flight plan data is identical to the strip described above regarding identification and flight level boxes. But beacons are now presented in a time-line, graduated in minutes (fig 2). The reference of the strip's time-line is a fixed point on the strip (reference time), corresponding to the present moment. This fixed reference point is located on the left hand side of the time-line. Beacons are placed on the time-line according to their estimate timing determined by the radar data obtained at the present moment. All strip time-lines have the same reference on the strip board, which is the present moment. Beacons are displayed chronologically on the time-line in the direction of flight. Time-lines and beacons move together throughout the flight from the right to the left towards the fixed reference point of the strip.

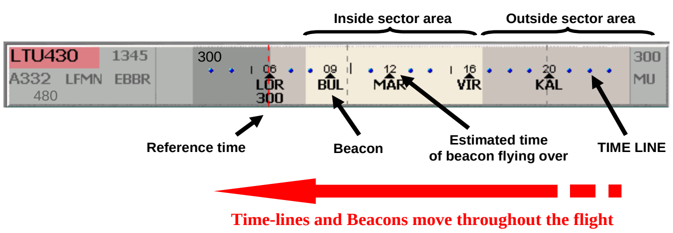


Fig 2. TimeLine presentation of flight plan data

B. *Working with TimeLine*

TimeLine flight plan data has the following characteristics:

The distance between beacons is strictly in line with the time required to fly the corresponding distance.

In a TimeLine strip board, a column corresponds to a given time, whereas in the traditional strip board, the position of beacons in a column has no special time-related meaning.

TimeLine provides an isomorphic representation of the distance flown according to time, rather than the "pseudo" geographical isomorphism found in traditional mode.

With a TimeLine strip board, it is easy without having to make any calculations, to anticipate the flight's trajectories, and therefore to analyze them. On a single time-related column (as well as between columns), the ATCO can know, at any time, without any calculation, the present and future position of different aircraft. ATCOs can now visualize air traffic as it flows. Furthermore, the controlled sector is highlighted in a specific colour, so the ATCO can easily anticipate inbound and outbound aircraft.

C. *Conflict identification*

The relative present and future position of aircraft in relation to specific navigation points are checked for possible conflicts. By comparing the vertical alignment of the different aircraft time-lines, the relative position of these aircraft can be visualized for that point in time. There are two conflict detection algorithms:

Vertical alignment of a same beacon for aircraft on crossing courses is characteristic of a merging conflict for aircraft flying at the same level.

Over speeding conflict is materialized by a sequence of identical beacons, with all or part of the route segment vertically overlapping at a given point in time. It is identified by sequences of overlapping identical beacons, when the interval between beacons is shorter for at least one of the aircraft.

IV. Experiment

A. *Procedure*

The experiment aimed to validate the usefulness of presenting flight plan data according to a time-line in a dynamic ATC simulation environment, by demonstrating that:

TimeLine makes it possible to understand traffic in a way that is at least as operative, if not more, than what is obtained with the traditional presentation mode.

TimeLine helps detect conflict at least as well as the traditional system.

Safety is as high, if not higher, with TimeLine in the case of heavy air traffic.

Guidance's may be elaborated in order to apply TimeLine concept in the frame of the further concepts ATM R&D (ASAS, A-MAN, D-MAN, E-MON, Highways, etc.)

The experiment compared the results achieved by operators in controlling air en-route traffic on a single-ATCO simulated working-position, when using both traditional and TimeLine presentation modes of flight plan data.

The simulation environment used the eDEP platform which is an EEC prototypal control working position platform. ATCOs give orders to aircraft's by radar screen. They are not pseudo-pilots. Control orders are immediately and automatically performed by the simulator.

Subjects were former civil and military ATCOs which had experience in tower, approach or en-route control. Now, all are working at EEC in an operational job.

The simulation was performed for each ATCO with both presentation modes. Two air traffic scenarios were built in order to avoid learning effect. Each run lasted 45 minutes. Before each test sequence, each subject was coached and trained to use TimeLine and traditional modes about one hour.

B. Variables

Independent variables:

Information presentation modes: traditional versus TimeLine mode

Nature of conflicts: existing conflicts and ATCO's order-triggered conflicts in order to honour aircraft's flight plan. In the former conflicts, the aircraft's are in conflict with another's when they enter in the sector of control, while in the latter, there is not conflict when aircraft's enter in the sector, but only when ATCOs give them orders to honour their flight plan. The latter conflicts require a bigger anticipation than the former to project the future states of the air traffic in the near future.

Scenario traffic loads with phases of light and heavy traffic.

Type of conflicts: over speeding conflicts versus merging conflicts. There were 2 over speeding and 2 merging existing conflicts, and 2 over speeding and 2 merging ATCO's order-triggered conflicts, i.e. 8 conflicts per traffic scenario.

Dependent variables:

Number of detected conflict (a range between 0 to 8 per scenario).

Times required by the subject to detect conflicts (subjects might say when they detected one conflict and what aircraft's were involved in the conflict).

Conflicts triggered by ATCO's orders independently of the scheduled conflicts (existing or ATCO's order-triggered).

CWP display (radar screen or strip board) used for detecting conflicts.

ATCO's workload assessed by NASA TLX. Workload was assessed at the end of each exercise.

ATCO's situation awareness assessed by simplified version of SASHA-Questionnaire. Situation Awareness was assessed at the end of each exercise.

Time spent by ATCO for managing and analysing strips.

Opinion of subjects collected during post-run interviews.

C. Experimental design

Sixteen subjects worked the experiment (3 females and 13 males). Subjects were from 9 different European countries, and they had a 13-years average experience of air traffic control.

Experiment was conducted according to a Latin square pattern: 2 groups of 8 subjects (G1, G2), 2 information presentation modes (P1 for traditional, P2 for TimeLine), 2 samples of traffic, to avoid learning curve effect between the two consecutive series of tests (E1 and E2). Each group is tested with the two information presentation modes one after the other, but in opposite order to offset any order effect.

V. Results

A. Conflict detection

Analysis of detected conflicts shows there is a significant difference between the two presentation modes (Chi2, p<0,001) for the number of detected conflicts (table 1). With the TimeLine mode, ATCOs detected more conflicts than with the traditional mode. Almost all ATCOs (15 out of 16) detected between 5 and 8 conflicts out of the 8 conflicts with the TimeLine mode, while only 3 ATCOs out of 16 were able to detect the same number of conflicts with the traditional mode.

An experiment hypothesis was to determine if one of the two presentation modes allowed ATCOs to early detect conflicts. The detection time is measured as from the moment when the flight plan data allowing to detect one conflict were displayed on the strip board and on the radar screen, and when ATCO identified the conflict. All conflicts were not detected by ATCOs, and sometimes no conflict was detected during the experimental run. Consequently, it is not possible to have a detection time value for this subject. This explains why the number of runs with traditional or TimeLine presentation modes is different from 16 in the "detection time" tables.

Even if ATCOs strive for spending less time to detect conflict with TimeLine, the difference between the two presentation modes is not significant.

TABLE 1
CONFLICTS DETECTION (EXISTING AND ATCO'S ORDER-TRIGGERED CONFLICTS)

Number of detected conflicts	***0 - 4***	***5 - 8***
Traditional strips	**13**	**3**
Time-line strips	**1**	**15**
Chi2 = 18,286	**P < 0,001***	

Detection time (seconds)	***< 200***	***> 200***
Traditional strips	**7**	**8**
Time-line strips	**11**	**5**
Chi2 = 0,1551	**P = Not Significant**	

Result of the first static time-line experiment was the time-line presentation mode increases the development of the traffic mental representation. In order to explore the level of mental representation (Endsley, 1995), two natures of conflicts were integrated in the experiment scenarios:

Existing conflict in which the conflict will occur without ATCO's orders

Conflict triggered by an ATCO's order in order to respect the sector exit instructions.

Detection of ATCO's order-triggered conflicts requires ATCOs have a better representation of the future aircraft's' states in the near future in comparison with the existing conflicts.

Experiment data show the existing conflicts detection is better with TimeLine mode than with the traditional mode (table 2), and the difference is significant (Chi2, p<0,01). Out of 4 conflicts to detect, 10 ATCOs did not detect or detected only 1 conflict with the traditional mode, while 10 ATCOs detected 3 or 4 conflicts with the TimeLine presentation mode.

Just like for the conflicts detection (table 1), the difference between the two presentation modes for the existing conflicts detection time is not significant, even if there is a tendency for a shorter detection time with the TimeLine mode.

TABLE 2
EXISTING CONFLICT DETECTION

Number of detected conflicts	0 -1	2	3 - 4
Traditional strips	10	4	2
Timeline strips	1	5	10
Chi2 = 12,808		P < 0,01*	

Detection time (seconds)	< 200	> 200
Traditional strips	6	4
Timeline strips	10	6
Chi2 = 0,016	P = Not significant	

Regarding the ATCO's order-triggered conflicts detection, the difference between the two presentation modes is also significant (Chi2, p< 0,001) in the same way (table 3). Ten ATCOs did not detect or detected only 1 or 2 conflicts with the traditional mode, while 15 ATCOs detected 3 or 4 conflicts with the TimeLine mode.

There is not significant difference between the two presentation modes for the ATCO's order-triggered conflicts detection time, even if, here too, there is a light tendency for a better detection with the TimeLine mode.

TABLE 3
ATCO'S ORDER-TRIGGERED CONFLICT DETECTION

Number of detected conflicts	0 - 1 - 2	3 - 4
Traditional strips	10	6
Timeline strips	1	15
Chi2 = 11,221		P < 0,001*

Detection time (seconds)	< 200	> 200
Traditional strips	6	8
Timeline strips	8	8
Chi 2= 0,153	P = Not Significant	

A more accurate analysis of experimental data allows identifying some aspects of the ATCOs' TimeLine use in order to detect conflicts. The low number of data doesn't allow establishing statistical data, even if the described tendencies are fruitful.

Regarding the conflict types (merging and overspending), the merging conflicts are detected easier than the over speeding conflicts, and this whatever the conflict natures (existing or ATCO's order-triggered conflict). This is similar for the two types of presentation modes.

The CWP has two displays (radar screen and strip board) for which it is possible to identify conflicts and this from one, regardless of the other. In the TimeLine presentation mode runs, the more used display for detecting conflicts is the strip board. Conversely, in the traditional presentation mode runs, the more used display for detecting conflicts is the radar screen. This tendency is the same whatever the conflicts nature and type.

Detection errors can also arise regarding the false detection of nonexistent conflicts. Even if these errors were at a very low rate, most of them occurred with traditional presentation mode (10 false errors) against 2 with TimeLine mode.

Experiment was built to detect conflicts integrated into standardized scenarios in which conflicts were scheduled. However, the control of traffic is a dynamic task in which the traffic continuously changes in relation with interactions ATCOs have with it. .Traffic understanding and the orders given at the aircraft by the ATCOs generate unscheduled traffic patterns in which unscheduled conflicts may occur. Of course, along the runs, such situations occurred, and it is interesting to notice less new conflicts occurred with TimeLine mode (9 unscheduled conflicts) than with the traditional presentation mode (18 unscheduled conflicts).

B. *ATCOs' workload*

The workload is the mental and physical cost required by the ATCO in order to perform the task of air traffic control. Workload is the ATCO's strain to cope with the constraints of the task, termed the taskload. Taskload features are stresses like traffic density and complexity, conflict nature and type, tool usability, etc. Taskload can be easily and objectively described while workload is more a feeling, a personal experience. The difficulty of workload measurement is to objectify this feeling.

In the experiment, the NASA-TLX technique was used. It was asked to the ATCOs to fulfil at the end of each run her/his opinion on the 6 NASA-TLX dimensions about what they experienced along the scenario achievement. The six NASA-TLS dimensions are: mental demand, physical demand, temporal demand, effort, performance, and frustration level.

Results show there is a significant difference on workload (ANOVA, p<0,001) between the two presentation modes (table 4). ATCOs assess lower levels of workload with the TimeLine mode than with the traditional presentation mode. There is not significant effect on the scenario type. The workload difference is consistent with the previous results about the number of detected conflicts and the tendency to detect faster the conflicts with TimeLine presentation mode.

TABLE 4
ATCOS' WORKLOAD DURING THE RUNS

NASA TLX	Scenario A	Scenario B
Traditional strips	70,750	60,375
Timeline strips	40,750	52,875
F = 20,785		P < 0,001*

C. ATCOs' situation awareness

Situation awareness is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future [12]. The situation awareness in Air traffic control is most of the time called "traffic picture". The ways to assess situation awareness are various. They are mainly based on either queries questioning or dimensions self-rating. The technique used in the experiment is a simplified version of the Situation Awareness for SHAPE Questionnaire -SASHA-Q (EUROCONTROL, 2006). Simplified SASHA-Q is made up of six items to self-rate along a 7 levels scale. Situation awareness is assessed by ATCOs at the end of each run following what they experienced during the scenario achievement.

Collected data show there is a significant difference on the situation awareness levels (ANOVA, p<0,001) between the two presentation modes. ATCOs assess higher levels of situation awareness with the TimeLine presentation mode than with the traditional mode. There is not significant effect on the scenario type. The difference on the situation awareness is consistent with the previous results about the number of detected conflicts and the tendency to detect faster the conflicts with TimeLine presentation mode.

TABLE 5
ATCOS' SITUATION AWARENESS DURING THE RUNS

SASHA-Q	*Scenario A*	*Scenario B*
Traditional strips	**3,394**	**3,393**
Timeline strips	**4,206**	**3,976**
F = 10,270		**P < 0,001***

D. Time spent by ATCO for managing and analysing strip board

A way for understanding how data displayed on the strip board are used by ATCOs is to measure and analyze the time spent by them for managing and analysing the strip board. During the experiment, ATCOs' gaze was registered by video. Then each run was counted according where ATCOs looked at (radar screen, strip board or another share). Results are presented following the percentage of time ATCOs spend on the strip board.

Results are really interesting because they show a significant difference (ANOVA, p=0,001) between the two presentation modes (table 6). ATCOs spent more time on the TimeLine strip board. In addition, the number of transitions between the strip board and the radar screen is significantly higher with the traditional presentation mode than with the TimeLine mode (ANOVA, p<0,001).

Such differences between the two presentation modes show that probably ATCOs find the data displayed on the TimeLine strip board are more useful for the air traffic control than the traditional strip board.

TABLE 6
TIME SPENT ON STRIP BOARD AND NUMBER OF TRANSITIONS BETWEEN THE RADAR AND STROP BOARD DISPLAYS

Time spent on strips	*Scenario A*	*Scenario B*
Traditional strips	**30,125 %**	**26,125 %**
Timeline strips	**36,000 %**	**36,750 %**
F = 23,868		**P = 0,001***

Radar/Strip transitions per minute	*Scenario A*	*Scenario B*
Traditional strips	**4,351**	**5,109**
Timeline strips	**3,456**	**3,939**
F = 34,084		**P < 0,001***

E. Debriefings

Subjects have all a favourable opinion for the TimeLine presentation. The advantages of TimeLine encompass several aspects of the ATCOs' activity:

The strip board management is more efficient with TimeLine. It is easier to analyze, compare and organize the traffic when new aircraft happen. The alignment of TimeLines strips, which occurs spontaneously and without any complex mental processing, provides a common reference for all aircraft', facilitating air traffic understanding.

This results in an ATCO's better traffic picture which favours greater traffic anticipation and planning. Conflicts are easier to detect and it is easier to quickly resolve them.

TimeLine advantages for detecting conflicts happen mainly for the over speeding conflicts, even if it is always difficult to detect this type of conflict. The extrapolation required to detect this type of conflict is simpler and quicker than with the traditional presentation.

With TimeLine, most of the conflicts are detected on the flight plan data when ATCOs analyze the strip board and look for understand the traffic. The use of traditional strips is different, the conflict being detected mainly in this case on the radar screen.

The use of TimeLine modifies the way ATCOs manage her/his activity between radar screen and strip board. New operating modes are required to understand the traffic and look for conflicts.

Transitions between radar screen and flight plan data are facilitated, ensuring a greater consistency and continuity in the way ATCOs manage the traffic. Some ATCOs qualified TimeLine presentation mode as being more user-friendly and more intuitive than the traditional mode.

Functional continuity between radar screen and TimeLine flight plan data results from the existing analogy between the time on the TimeLine strip and the distance on the radar screen. This functional continuity is also improved by the fact the TimeLine data are continuously upgraded by the radar data.

When traffic is heavy, the feeling to have a good traffic picture remains longer with the TimeLine mode than with the traditional, but it is always difficult to work with strips. Tendency is to work only with radar screen, even if time horizon becomes short-term. With medium traffic density, more things are perceived with TimeLine.

In heavy traffic density situations, the use of TimeLine stays difficult for the executive controller, just like with traditional presentation mode. But TimeLine could be an efficient tool to facilitate in these conditions, the work of the planner controller.

The mental effort resulting from the TimeLine use is not greater than what is required with the traditional mode. It is even lower. ATCOs' remarks were mainly that less calculation is required, less data need to be manipulated, that fatigue is decreased and that TimeLine requires less concentration and less deep thought. ATCOs say this is probably due to the fact the information is pre-processed in TimeLine because there is an analogue presentation.

The time to be familiar with the new concept is fast. The training is easy and intuitive. After few practice, it is possible to easily find an efficient way to use the TimeLine strips.

VI. Discussion

The results of the TimeLine dynamic experiment show there is a significant difference between the two modes of flight data presentation. TimeLine mode allows detecting more conflicts whatever the types and the nature of conflicts. This results is reinforced by the significant difference with which ATCOs assessed TimeLine regarding workload and situation awareness. We can say safety and performance are improved with TimeLine for managing air traffic.

TimeLine presentation has a great advantage in medium traffic load. It is allows ATCOs being more efficient with heavy traffic density in order to keep the possibility to anticipate and plan the traffic. However, when the traffic load is very heavy, the flight plan data cannot be used and the traffic management is only led in the very short-term time horizon.

If the TimeLine concept is useful for the executive controller, it seems it will be very useful, too, for the planner controller which is in charge of the medium and long term time horizons. The experiment did not investigate the issue of the TimeLine use by the planner, and this might be a focus in the future.

Quantitative data confirm the ATCOs feelings about TimeLine. The TimeLine advantages are clearly linked to the ways the controllers perceive and process flight plan data. The way the information is displayed allows ATCOs being more comfortable, more intuitive with the traffic understanding and the conflict detection. Traffic mental representation with TimeLine is complementary with the radar representation. By being able to anticipate properly the traffic on the TimeLine strip board, the radar screen job is facilitated and it is more efficient. The time spent by the controllers on the TimeLine strip board confirms the used operational modes. Similarly, the lower number of transitions between the radar screen and the TimeLine strip board emphasizes ATCOs have more confidence in the TimeLine strip board. They are able to spend more time on the TimeLine strip board without looking at the radar screen which is the primary tool for the safety. In addition, the time they spend on the TimeLine presentation mode means they are able to deeper understand the traffic on this display. The safety and confidence feeling is reinforced by the complementarities of the two displays which allows easily passing from the one to the other.

In this sense, TimeLine actively participates to better situation awareness and a lower workload which increase the level of control ATCOs have on the traffic. By this way, TimeLine can be envisaged as a major safety enhancing tool.

TimeLine was developed along the lines of an analogue representation of the flight data. Operational modes used by ATCOs for identifying conflicts and looking for solving strategies demonstrate that it is possible to work with TimeLine in the logical and mathematical mode. This operational mode is more consuming than the perceptive mode, but it is interesting because it can be used as an alternative to provide new insights when the traffic is difficult to understand from the onset. This alternate mode also provides ATCOs with additional adaptation margins in their routine work, thus contributing to maintaining the safety level. TimeLine thus appears as a representation mode combining both analogue and symbolic characteristics, allowing the perception-based processing characteristic of radar work, and logical and mathematical operations, characteristic of traditional flight plan presentation mode.

The experiment was generic in the sense ATCOs' job was relatively far from an operational setting. However, conclusions are very positive to pursue TimeLine investigations. However now, new developments require envisaging concrete applications. The experimentation results emphasize some ways to develop TimeLine concept:

Firstly, the TimeLine concept appears to be very useful for managing aircraft sequencing. Most applications may candidate for its use like the approach and runway sequencing. It can be also envisaged in the frame of tools like departure, arrival or en-route managers. Some ATM concepts like ASAS, 4D-trajectory, Highways or Contract-based ATM are relevant for using this type of flight plan data. Similarly, the complementarities between TimeLine and MTCD tool must be envisaged for an efficient application.

Lastly, TimeLine concept must be envisaged with the planner controller's job. Task sharing between executive and planner controllers, dedicated interfaces and common tools are issues which have to be tackled in the future stages of the TimeLine development. For instance, a TimeLine concept-based inbound list of aircraft entering the controlled sector could be a relevant application for the planer controller. Finally, TimeLine concept could be also considered, for instance, like a useful tool for a Multi Sector Planner.

VII. CONCLUSION

The dynamic experimental assessment of the TimeLine concept confirms the first results of a static experiment carried out in 2003 at EEC. The results, despite a generic simulation platform and ATC task, show significant advantages in the use of the TimeLine concept in comparison with the traditional flight plan presentation mode. Better conflict detection, better situation awareness, and lower workload are the main results to justify such a conclusion. These improvements result from a better mental representation of air traffic in relation with the way the flight plan data are displayed on the TimeLine presentation mode. TimeLine combines both analogue and symbolic characteristics favouring transitions with radar screen. The ATCOs ' feeling of comfort and confidence is increased with TimeLine. Now, future developments of the concept require applying it in concrete situations linked to existing or future operational ATM concepts.

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Effects of Alternative Taxiing Procedures on Airport Operations

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***Abstract*— This analysis dealing with different taxiing procedures shows that the implementation of aircraft using Alternative Taxiing (AT) procedures, such as operational towing or use of powered landing gear, do not cause large-scale changes in airport operations, especially when alternatively driven aircraft are taxiing with a speed not deviating significantly from the speed the aircraft operating Main Engine Taxiing (MET) use. By modifications of infrastructure layout even positive effects perceive in some sections.**

Index Terms—**Simulation, Airport, Operations, Taxiing, Main Engine Taxiing, Alternative Taxiing, Capacity**

I. Introduction

NOWADAYS aircraft roll from the gate to the runway by the power of main engines. As main engines have an extremely low efficiency at idle power, this is a very ecologically and economically unfriendly way to move an aircraft on an airfield. Because kerosene is not burned in an optimal way, in this flight phase disproportional high values of carbon dioxide (CO), unburned hydrocarbon (UHC) and nitrogen oxides (NO_X) are exhausted by aircraft and strongly influence the local air quality of the airport and the surrounding area.

Currently various Alternative Taxiing (AT) concepts are investigated, for example taxiing with a powered nose landing gear using power of the Auxiliary Power Unit (APU) or towing of aircraft with a tug over long distances instead of using Main Engine Taxiing (MET) (see Virgin Atlantic Airways, 2007; WheelTug, 2007). The reasons why this concept is of interest to the industry are the fuel savings and emission reductions that could be achieved during this flight phase, especially in today's climate change debate.

AT with similar speeds as MET requires a need for high power of nose landing gear motor or tractor, which causes high weights and costs. Therefore the speed requirement shall be kept to the necessary minimum. As a consequence, the performance of the system needs a detailed study of airport operations.

II. Objective of Investigation

Whereas many investigations about technical practicability of these AT procedures with single aircraft are already underway, there is not yet sufficient knowledge on how AT procedures with slowly taxiing aircraft affect airport operations as a whole, e.g. by obstructing the way to faster aircraft.

On one hand the required maximum speed must not be so slow to be a disturbing obstacle to other aircraft and on the other hand not so high that high cost and weight are needed without further operational benefit. Otherwise the advantages of AT procedures cannot be exhausted completely. As a result AT aircraft should drive with a taxi speed that does not influence airport operations, in particular does not constrain the taxi phase of aircraft moving with engines and that does not change significantly the total taxi duration.

III. Simulation Tool

In order to investigate the effects, which occur by the implementation of AT procedures on airport operations, simulation models were built up to simulate the changed ground traffic flow.

The simulation tool used is the discrete-event simulation SimmodPLUS (see ATAC, 2007). This simulation tool needs detailed information about the airport geometry and the flight operations considered. The airport models are based on the detailed AIP maps with all points and distances at the airport, consisting of the actual layout of the airports with all gates, taxiways and runways and relevant flight routes (see DFS, 2007, EDDL; LVNL, 2007, EHAM). All of the airside flight tracks and ground paths are divided into links and nodes, which form a complex network. Links and nodes have to be specified in detail. Different taxi speeds were defined for different aircraft types for each trajectory segment within the SimmodPLUS input tables.

IV. Simulation Scenarios

Simulations of airport operations were done for two different cases: The simulation model of Düsseldorf International Airport (DUS) represents a typical European mid-size airport (16,60 mio. pax) with an average taxiway length of 2 to 3 km. In this research the taxiing procedures from the actual gate positions as well as from the various remote positions to the main departure runway 23L (Südbahn) are considered. In this scenario runway 23L is used for departures, the parallel runway 23R for arrivals only. The second simulation model of Amsterdam Schiphol Airport (AMS) represents a European major hub (44,20 mio. pax) with a very long taxiway system, typical taxiing distances being 6 to 9 km. In order to highlight these effects of extremely long taxiways with a much higher taxi speed, the taxiing procedure from the different pier and remote positions to the new departure runway 36L (Polderbaan) was chosen for this analysis. In the selected runway mode aircraft are not allowed to cross the parallel runway 36C (Zwanenburgbaan), which is also used during this time. This mode causes an extremely long taxiing procedure for aircraft departing from 36L, so this mode is suited as a worst case for this analysis.

In both cases, DUS and AMS, a whole busy day was simulated, with times recorded from actual flight records. So the simulations are based on the peak day of 2005 of DUS and a busy day (traffic near to the peak day) in 2006 of AMS. From these flight plans result an air traffic volume of 321 departure flights of runway 23L at DUS and an air traffic volume of 471 departure flights at 36L at AMS. Whereas both flight plans mainly consist of flights with narrow body aircraft, Fig. 1 shows that differences occur for the other aircraft categories. As AMS is an international major hub with a high number of intercontinental flights and a main focus on air cargo, the percentage of large, heavy aircraft is much higher than in DUS where regional aircraft take an important part of the daily air traffic volume.

		Airport	
		DUS	AMS
Aircraft Class	Regionals (CRJ, E145, F50...)	33%	21%
	Narrow Bodies (A320, B737, F100...)	60%	62%
	Wide Bodies (A330, A340, B777...	7%	12%
	Two-deck Aircraft (B747)	0%	5%

Fig. 1. Traffic Mix at DUS and AMS

As shown in Fig. 2, two classes of aircraft are considered in the simulation scenarios. On the one hand there are faster aircraft using classical MET and on the other hand there are slower aircraft using the innovative AT method. To find the optimal speed range, AT taxiing speeds of 10 and 14kn were used in the simulations. Various combinations of speeds and mixes between aircraft classes were considered. In this context the ratio between aircraft operating MET and AT changes with increased market penetration of new aircraft capable of performing the new taxiing procedure. The representation of varying market penetration of AT aircraft (in 5 steps) is obtained in the simulation by attributing the AT procedure to one or more groups of aircraft of the same type (e. g. all A320 family aircraft). Since presumably these new technology will initially be implemented to narrow body aircraft, due to technical and environmental requirements, this investigation basically focuses on the market penetration of this aircraft category. This stepwise approach leads to a total number of 32 different simulation scenarios, with a mix of different taxiing procedures, different market penetrations and different taxi speeds.

			Airport Scenario		
			DUS - 10kn	AMS - 10kn	AMS - 14kn
Taxiing Scenario	Scenario 1	MET	100%	100%	100%
		AT	0%	0%	0%
	Scenario 2	MET	68%	79%	79%
		AT	32%	21%	21%
	Scenario 3	MET	48%	33%	33%
		AT	52%	67%	67%
	Scenario 4	MET	16%	12%	12%
		AT	84%	88%	88%
	Scenario 5	MET	0%	0%	0%
		AT	100%	100%	100%

Fig. 2. Simulation scenarios of DUS and AMS

Beside the fact that the aircraft using AT roll slower, they moreover need a so-called engine-run-up area in order to start their engines and to execute various check lists before they get take-off clearance. This process at the head of the runway takes about 3 to 5min. In order to ensure a smooth handling of the taxiing traffic, a modification of the airport infrastructure is required in any case: At both airport scenarios a second departure queue is adapted, using already existing runway entrance taxiways, where all the aircraft using AT can wait and do their engine start on a starting grid with a total capacity of 3 aircraft. Moreover a separate service road for towing tugs to drive back to the apron is assumed, since a concept where aircraft and tugs share the same infrastructure does not seem realistic.

Fig. 3. Simulation model of AMS

As the key challenge of the simulation is to see the different effects on the taxiing and waiting time for both, aircraft operating MET and AT, this point is focussed in the following analysis. Here especially the obstruction of aircraft which are operating MET caused by alternatively driven aircraft is of main interest. Another aspect is to see the effect on the hourly throughput at the airport, which is an important parameter for an economic evaluation. All these resulting effects are analysed as a function of taxiing speed and mix of aircraft categories. Using these results it shall be possible to define an optimal speed range.

The research is therefore divided into two major parts: Part 1 deals with finding a reasonable minimum AT speed range. Part 2 of the analysis concerns the question to which extent airport operations and aircraft using MET are affected by the aircraft using AT.

V. Results

In order to analyse the effect caused by different taxi speeds, aircraft operating at the two airports DUS and AMS are assigned different taxi speeds in the range of 10 to 30kn. This first part of the research mainly highlights general aspects of the taxiing processes on airfields, lead to universally valid conclusions concerning taxiing.

Taxi speed [kn]	Total taxi time [min]		Rolling time [min]		Waiting time [min]	
	DUS	AMS	DUS	AMS	DUS	AMS
10	12,87	34,91	11,43	29,46	1,45	5,51
14	11,43	30,14	10,01	24,45	1,44	5,74
18	10,71	27,42	9,19	21,67	1,53	5,80
22	10,24	25,71	8,67	19,90	1,58	5,87
26	9,88	24,10	8,31	18,67	1,58	5,48
30	9,60	23,59	8,05	17,77	1,57	5,87

Fig. 4. Total taxi time using different taxi speeds at DUS

Fig. 4 shows the effects of using different speeds for taxiing. 10kn is the lower limit and rarely used in practice for taxiing long distances, and 30kn is the upper limit due to restrictions of the aircraft manufacturer concerning aircraft brakes. The taxi speed that is chosen by the pilot depends on many different factors: On one hand there are infrastructural factors like airport layout, number of intersections, taxiway length and visibility, on the other hand there are restrictions from legislation, airports, airlines or aircraft manufacturers that limit the choice of the taxi speed.

Taxi times obtained by simulation agree very well with observations and actual times from flight plan records including actual off-block and runway times. It results that aircraft at DUS taxi with a medium speed of about 14kn, whereas the aircraft at AMS are able to use high speed taxiways and so taxi with a much higher medium speed of about 22kn. From this it results that aircraft at a mid-size airport like DUS with short and curvaceous taxiways and a high number of intersections taxi much slower than at a major hub airport like AMS with much longer and straight taxiway sectors without intersections and good visibility conditions.

As one more result we see in the figure that significant taxi time changes are reached by varying the taxiway speed between 10 and 14kn at DUS or from 10 to 22kn at AMS. At AMS e.g. the taxiing process is accelerated by more than 4,5 min by using 14kn for taxiing instead of 10kn. As we see in the following, the further rise of taxi speed beyond 22kn has no significant effect. At DUS the same effect occurs beyond 14 kn. As the effective taxi time (rolling time) decreases continuously by using higher taxi speeds, in contrast the waiting time increases and leads to only small improvements in the total taxi time. The faster the aircraft taxi, the more time the aircraft spend in the departure queue. The percentage of the waiting time relative to the total taxiing time shifts from 15% (10kn) to 25% (30kn). We notice that faster aircraft do not inevitably accelerate the taxiing process significantly. Beyond a certain speed level, aircraft spend more time in the departure queue and less time for the actual taxiing procedure.

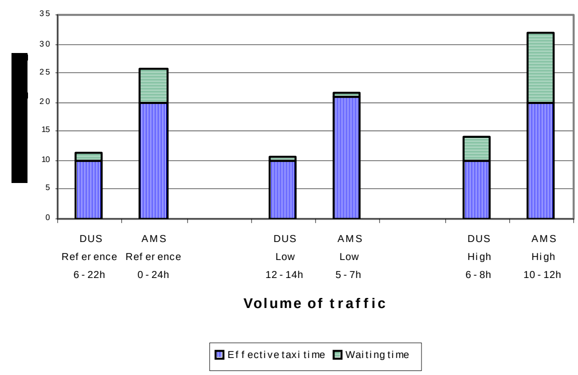

Fig. 5. Variability of total taxi times depending on volume of traffic at DUS and AMS

In the simulation, aircraft use different gate and remote positions. Here only average values are shown for total taxi time, rolling time and waiting time in departure queue. As the effect of lost waiting time in the departure queue is such an important point in this analysis, it is necessary to analyze this phenomenon in more detail. As we can see in Fig. 5, the total taxi times vary significantly over the day due to high or low volume of traffic. At DUS this traffic peak appears in the period from 6 to 8h, while at AMS traffic reaches its departure peak at the term of 10 to 12h due to its hub function offering a large number of intercontinental traffic. While the effective taxiing time on the taxiways stays constant during the day, the increased waiting time in the departure queue is mainly responsible for the increase of total taxi times during peak hours. During peak hours at AMS time in the departure queue takes about 12min, whereas DUS reaches values of about 5min.

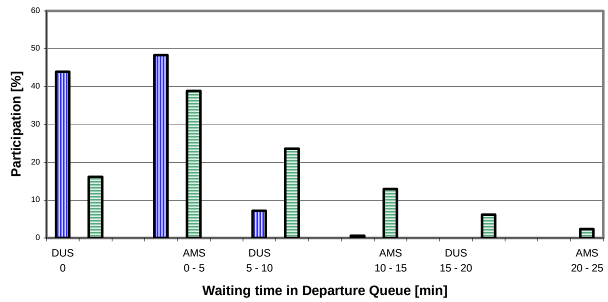

Fig. 6. Histogram of waiting times in departure queue at DUS and AMS

As the effect of waiting time in the departure queue is so important in this context, it is necessary to focus how often this phenomenon actually occurs during a day. As we can see in Fig. 6 there are, especially at AMS, not many aircraft that achieve the runway without staying in the departure queue for a couple of minutes. From 471 aircraft departing from Amsterdam 36L only 76 aircraft (16%) are able to pass the departure queue without any waiting time. The other 395 aircraft have to stay in the departure queue for more or less time. While aircraft at DUS spend mainly no time (44%) or up to 5 minutes only in the departure queue (48%), aircraft at AMS reach much higher values up to 20min waiting time.

Part 2 of the analysis deals with the question to which extent aircraft using MET, i. e. airport operations, are affected by aircraft using AT. Because the implementation of alternatively driven aircraft is strongly related to power requirements and therefore to weights and development costs, it is of great importance to find an optimal taxi speed range for these aircraft. When aircraft using AT are too slow, they slow down the whole taxiing process and form a disturbing obstacle to other aircraft. On the other side it is penalising to install heavy and powerful motors - from which a higher fuel burn during the much longer flight phase will follow - or to purchase expensive powerful tugs to ensure a high speed of the alternative driven aircraft. As a result AT aircraft should drive with a taxi speed that does not adversely influence airport operations, in particular does not constrain the taxi phase of aircraft moving with engines and does not change significantly the total taxi duration. To see these effects the data shown in Fig. 7 and 8 were evaluated.

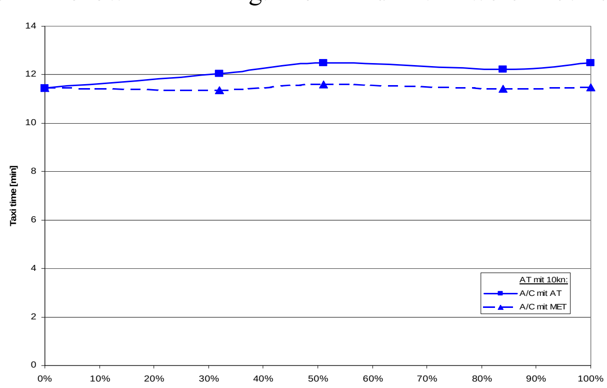

Fig. 7. Taxi times of A/C using MET and AT at DUS

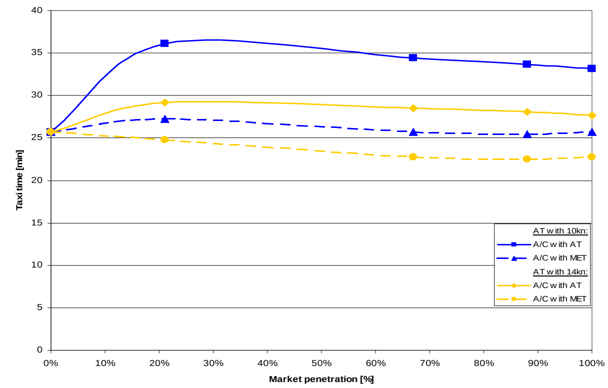

Fig. 8. Taxi times of A/C using MET and AT at AMS

The fact that the average taxi speed at DUS is only 14kn lead to the assumption that aircraft taxiing with 10kn will not affect ground operations as much as it supposedly does at an airport with high speed taxiways, like AMS. In case that aircraft using AT are able to taxi 14kn there would even be no negative effect on airport operations, because this speed conforms to the expected speed of aircraft using MET at this mid-size airport. In Fig. 7 and 8 the total taxi times of the different taxiing procedures are considered, whereas the time of engine run-up is not regarded in these values, making more sense for a comparison. As we can see, at DUS the taxi time of aircraft using AT increases by only one minute from 11,43min (market penetration 0%) to 12,49 minutes with 100% of all narrow body aircraft using AT. Aircraft using MET are not significantly, or even not at all affected by the slower taxiing aircraft. Their total taxi time remains practically constant (11,43/11,47min). On one hand times are not significantly increased because there is only a speed difference of 4kn, on the other hand the effect of creating a second departure queue in the area of the bypass taxiway releases the main departure queue at the end of the runway and leads to this effect. By analyzing AMS (see Fig. 8) we can see the effect that aircraft using MET are taxiing much faster (22kn) than aircraft using AT with 14 or even 10kn. Aircraft using AT with only 10kn have a much longer taxi time of up to over 36min (21% market penetration). The reason why this value decreases again with increasing market penetration is due to the maximum deadlock-effect that is caused when there is a high mix of different taxiing speeds. In comparison with the reference scenario of taxiing with 22kn the taxi time increases by more than 10min during the long taxiing distance of AMS. Similarly to the DUS case, there is no increase of the total taxi time of aircraft using MET, although these aircraft are obviously obstructed by the 8kn slower alternative driven aircraft. Their taxi time stays on a constant level of about 25 min for all market penetrations.

Moreover the figure demonstrates a significant difference in taxi times between the scenarios with AT speed of 10 and 14 kn. Whereas for aircraft using MET this difference is less than two minutes, AT aircraft are slowed down by up to 6 min. It is pointed out that the taxi time of aircraft using MET is even influenced in a positive way by introducing AT with a taxi speed of 14kn. Their total taxi time is reduced from 25,71min to 22,74min at 100% market penetration; however, this effect is mainly due to the installation of a second departure queue.

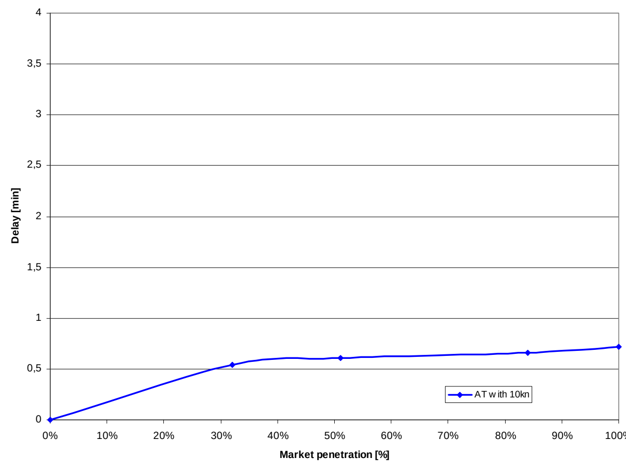

Fig. 9. Delay of A/C using MET caused by A/C using AT at DUS

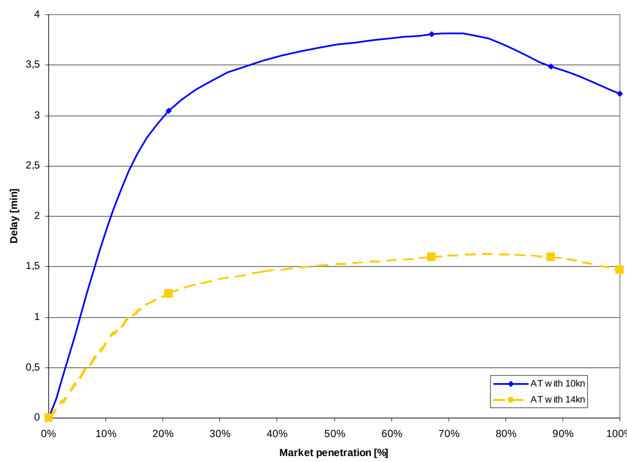

Fig. 10. Delay of A/C using MET caused by A/C using AT at AMS

To evaluate the hindering effect of slow AT aircraft it is important to see to which extent aircraft using MET suffer a delay during the taxiing distance. This means on one hand how often does the case occur that a faster taxiing aircraft drives up to a slowly taxiing aircraft, and on the other hand how much delay this might cause for the aircraft using MET.

At DUS the case that fast taxiing aircraft drive up to slowly taxiing aircraft does not appear far often. Because of the short taxiway system of only 2 to 3 km and a relatively small speed difference of only 4kn the aircraft using MET are not affected in a strong way – particularly during low traffic times. Their rolling time is only decelerated by less than one minute by implementing AT for all narrow body aircraft. As we can see in Fig. 10, the implementation of aircraft using AT has a stronger effect at AMS, although it is to be differentiated between the scenarios that aircraft do AT with 10 or 14kn. Whereas aircraft using MET are slowed down by aircraft taxiing alternatively with 14kn by only 1,5min, these aircraft are much more hampered by aircraft which are taxiing alternatively with only 10kn. Here it appears more often that fast taxiing aircraft drive up to slowly taxiing aircraft, caused by the big speed difference of 12kn on a long taxiway system of several kilometres. When there is a market penetration of 100%, "tailgating" of aircraft takes place in 251 cases and causes a total taxiing delay of 3,2min for aircrafts operating MET.

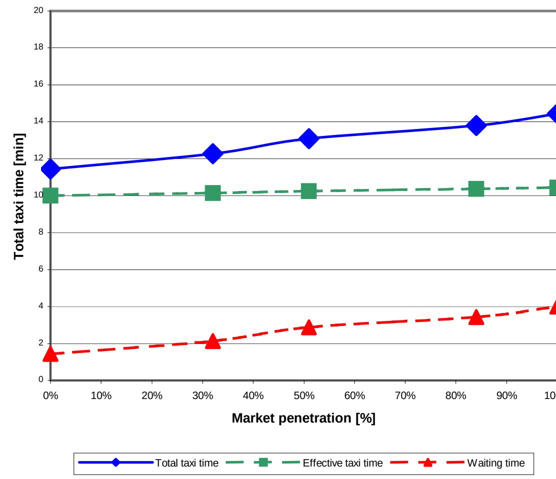

Fig. 11. Average total taxi, rolling and waiting time (incl. engine run-up) as a function of market penetration at DUS

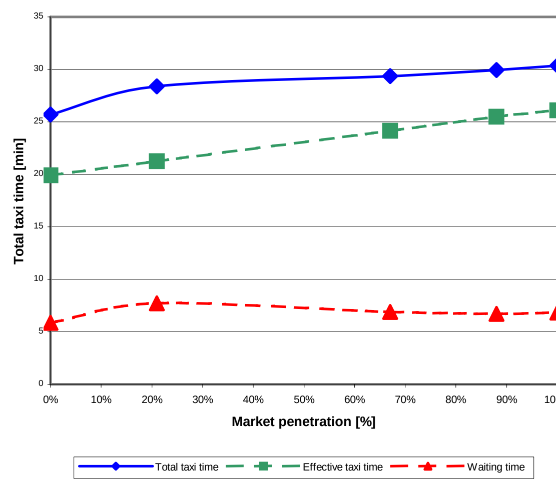

Fig. 12. Average total taxi, rolling and waiting time (incl. engine run-up) as a function of market penetration at AMS - 10kn AT

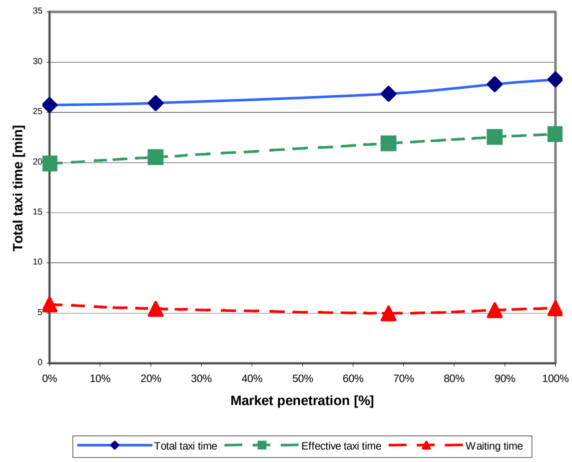

Fig. 13. Average total taxi, rolling and waiting time (incl. engine run-up) as a function of market penetration at AMS - 14kn AT

As shown in Fig. 11, at DUS the average total taxi time of all aircraft increases by 3 min from 11,43min (market penetration 0%) to 14,44min (100%). This increase is not caused by a slow down of the taxi process, which stays more or less constant equal at about 10min. The reason for the increase is strongly related to the lengthening of the waiting time in the departure queue, which is caused by the required time for engine run-up on the starting grids. Because at the mid-size DUS Airport there are no or relatively short departure queues, this time preponderates in this scenario (see Fig. 1). The waiting time is extended from 1,44min. (0%) to 4,01min (100%), which corresponds approximately to the time for engine run-up (3 – 5 min). At the hub airport AMS another effect is visible, especially in the case of AT aircraft with 14kn (see Fig. 12). In this scenario the total taxi time of all aircraft increases from 25,71min. (0%) to 28,27min. (100%). In contrast to the DUS scenario, here the rolling time increases from 19,90min. (0%) to 22,83min. (100%), due to the long taxi distance of several kilometers, whereas the waiting time in the departure declines in this scenario from 5,89min. (0%) to 5,49 min. (100%). As already mentioned this is an effect that coheres with the implementation of a second departure queue for aircraft that have to start up engines first in the area of the beginning of the runway. Because aircraft are separated in this area and would have to wait anyway before reaching the runway for a time of about five minutes (see Fig. 2), aircraft have to stay even half a minute less in the waiting queue in comparison to the reference scenario. Fig. 13 shows the same tendency by aircraft using AT at AMS with 10kn but not in such a distinctive way as in the scenario with 14kn. Here the total taxi time increases from 24,71min. (0%) to 30,37 min. (100%), whereas this lengthening of the taxiing process is also mainly caused by a much longer rolling time with a low speed of only 10kn. In comparison to the reference scenario, the rolling time is increased by more than 6min. In contrast to this, the waiting time is only increased by about one minute.

Another very important parameter analyzed is the effect on the hourly throughput at the two considered airports. The hourly throughput is the number of aircraft that take off within one hour after the indicated time in Figs. 11 and 12.

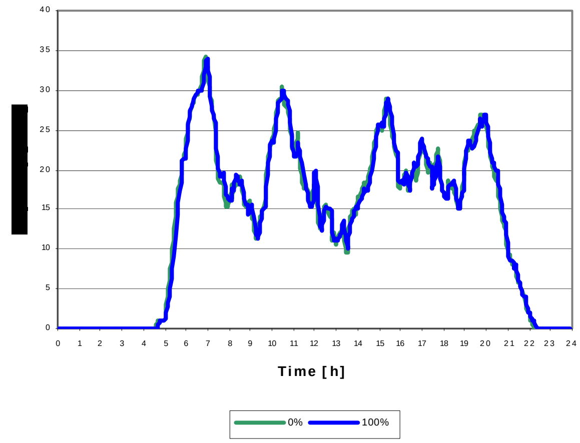

Fig. 14. Hourly throughput at AT market penetration of 0 and 100% at DUS

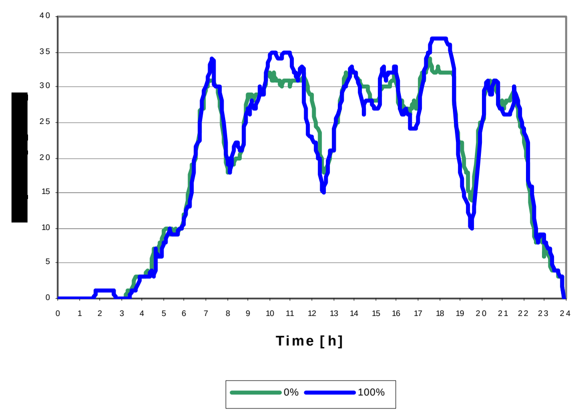

Fig. 15. Hourly throughput at AT market penetration of 0 and 100% at AMS

As we see, at DUS the hourly throughput does not vary by introduction of AT. In both scenarios with market penetration of 0 and 100%, the maximum value of departing aircraft goes up to 34 aircraft at the morning peak from 6 to 8h. At other peak time frames the same effect occurs. The number of starting aircraft stays on a constant high level, while there is just a time lag of a couple of minutes in comparison to the reference scenario. As we already see in Fig. 11, the aircraft are just arriving at the runway entrance approximately 3min later, so the graph of hourly throughput is simply shifted by this time amount. The hourly throughput is the same as in the scenario with a market penetration of all narrow bodies taxiing alternatively. Contrary to DUS, the implementation of the AT procedure at AMS even has a positive impact on the hourly throughput. For example we see during the morning peak from 10 to 12h three additional aircraft can depart per hour if 100% of all narrow bodies use AT instead of MET. Here the high traffic volume is transacted in a shorter period of time, while in the reference scenario the peaks have a flat and broad look. The same effect is observed at the evening peak from 17 to 19h, when there are 37 aircraft able to depart instead of 34 in the reference scenario. Doubtless the reason for this surprising observation lies in the handling of the traffic with two separate departure queues, with one queue for aircraft taxiing with Main Engines and another queue for aircraft using AT. Although these aircraft have to drive through the bottleneck of a starting grid for the engine run-up, the whole process is accelerated and the capacity increased.

VI. Conclusion

As a first result of the analysis, faster aircraft do not necessarily accelerate the taxiing process significantly. At a certain speed level aircraft spend more time in the departure queue, whereas slower aircraft shift the waiting time into the departure queue to the taxiway by rolling slower. This diagnosis leads to the conclusion that the range of most efficient taxi speeds is between 14 and 22kn, due to the relation of rolling time and waiting time for most airports. As a result a faster speed of more than 22kn would not lead to significant improvements in the field of total taxi time.

The technically realistic speed assumptions of 10 and 14kn for aircraft using AT have been analysed more in detail. An AT speed of 14kn has shown to cause no significant adverse effects on other aircraft operations. At small, mid-size or blind bend airports with slow taxiing procedures it even conforms to the already existing taxi speed of aircraft using MET. For this slower taxiing procedure aircraft need much less power to move, which is a very important point in designing a required speed range for alternatively driven aircraft.

Especially during peak hours AT aircraft constitute no significant obstacles, because then aircraft spend most of their total taxi time in queuing. However, at other times slower taxiing aircraft hinder the airfield traffic flow, particularly when there are no or just short departure queues. In low traffic times the decelerated taxiing procedure and the engine run-up time cause a delay of many minutes for the AT aircraft.

The conclusion is that the implementation of alternatively driven aircraft taxiing with 14kn in fact causes a loss of time, but constitute an overall satisfying solution for alternatively driven aircraft, regarding total taxi times, delay of AT and MET aircraft and airport capacity.

In contrast to this, a speed level of only 10kn for aircraft using AT causes significantly negative effects on airfield operations, especially on the rolling time on airports with a long taxiway system. Moreover it often comes to the undesirable effect that faster MET aircraft drive up to slower AT aircraft. Because they are unable to overtake these slow objects on the taxiway they also accumulate a delay of several minutes. Because of these negative effects a choice of speed level of 10kn is absolutely unacceptable.

Regarding the hourly capacity, there are no negative effects recognizable by introducing aircraft using AT. In contrast, even a positive impact on the hourly throughput is perceivable by an adaptation of the airfield infrastructure, e.g. by implementation of a second departure queue of aircraft using the engine run-up area. In this airport area, departure separation according to Air Traffic Control rules represent the limiting factor, but not the choice of taxiing procedure.

To evaluate the gains of alternative taxiing procedures there is also the issue of evaluating the environmental benefit of reduced engine emissions. The interest lies in the opposite influence of emission reduction by AT procedures and emission increase by longer taxiing times or using APU. The present study gives input data on realistic taxi phase durations and speeds, which are necessary to do such an investigation..

Acknowledgment

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Augmented Vision Videopanorama System for Remote Tower Operation: Initial Validation

N. Fürstenau, M. Schmidt, M. Rudolph, C. Möhlenbrink, B. Werther

Abstract— **In this paper an experimental high resolution video panorama system for remote tower operation (RTO) is described and results of initial field test are reported. The reconstructed far view with integrated zoom function serves as main information source for surface movement management of small airports by a remotely located tower controller. It provides the framework for video-see-through augmented vision by integration of flight data and it allows for panorama replay. Evaluation of initial field tests yields the effective visual resolution of the 180°-video panorama in agreement with the theoretical prediction and slightly reduced as compared to the real far view from the airport tower.**

***Index Terms*—Airport tower, remote operation, video panorama, augmented vision, work analysis, field tests**

I. Introduction

REMOTE Tower Operation (RTO) describes the goal of surface movement management of one or more small airports from a remotely located control center without direct far view to the airport surface. Because small airfields usually lack any advanced electronic surveillance system a high resolution augmented vision video panorama as a potential low cost system is proposed to replace the direct far view out of the tower windows as main component of the Human Machine Interface (HMI) [1][2].

A number of tower work analyses performed during the recent years determined visual surveillance to be the most important activity of tower and apron controllers for creating their situational awareness, despite the availability of electronic surveillance [3][4]. In the tower environment of large airports the permanent refocusing between far view and displays contribute to the workload and increases head-down time which may both be reduced by a high resolution panorama display with distance to the operator comparable to radar and flight data displays. Consequently it is assumed that under the guideline of human centered automation, the reconstruction of the far view from the control tower of small airports will improve the transition process to a towerless work environment and make it acceptable to the remotely located RTO controller. Within the DLR project RapTOr (Remote Airport Tower Operation Research) an RTO experimental system is realized at the Braunschweig research airport [1][2]. It is accompanied by a structured work and task analysis [5] and model based simulations of controller's decision processes [6]. A 180° video panorama system was developed as core of the RTO controller's HMI. For designing a compact RTO work environment video see-through augmented tower vision (ATV) is realized by integrating information from real time image processing and electronic surveillance sensors like multilateration into the digital videopanorama. ATV has been proposed by several authors before, however aiming at augmenting the real far view by means of optical see through head mounted displays, e.g.[8]. Recently initial ATV demonstrations with superimposed information in the real tower environment have been performed [1] by using a head-up holographic backprojection display [11] [12].

In section 2 the tower work analysis and development of model based simulation are outlined which support the RTO HMI design. Section 3 describes the augmented vision video panorama system as basis of the experimental RTO system. Results of field trials are described in section 4. Section 5 provides a conclusion and outlook.

II. Work Analysis and Model Based Simulations

The design and development of the new Remote Controller work environment is supported by a formal cognitive work and task analysis (CWA) [5] by means of structured interviews of domain experts (controllers) from medium sized and small airports [6]. The formalised results serve as input data of a Formal Airport Control Model (FAirControl) for the simulation of the controller decision making processes at the tower work positions. In [9][10] it is shown how the results of a CWA on a medium size airport are transferred into an executable human machine model, based on Colored Petri Nets (CPN) [7] for simulating the controllers work processes in relation to the airport processes. The executable model supports the identification of controllers' strategies in task organization and pursuance of goals. The formal model serves for evaluation of different variants of work organization, supports the design of the new work environment and the monitoring of psychological parameters, e.g. uncovering of reduced situational awareness. The simulations in turn support the extraction of detailed expert knowledge during interviews with the controllers and they provide input for the human interface design. As depicted in Fig. 1 the human machine model is separated into submodels for the human (controller), interaction, and the traffic process.

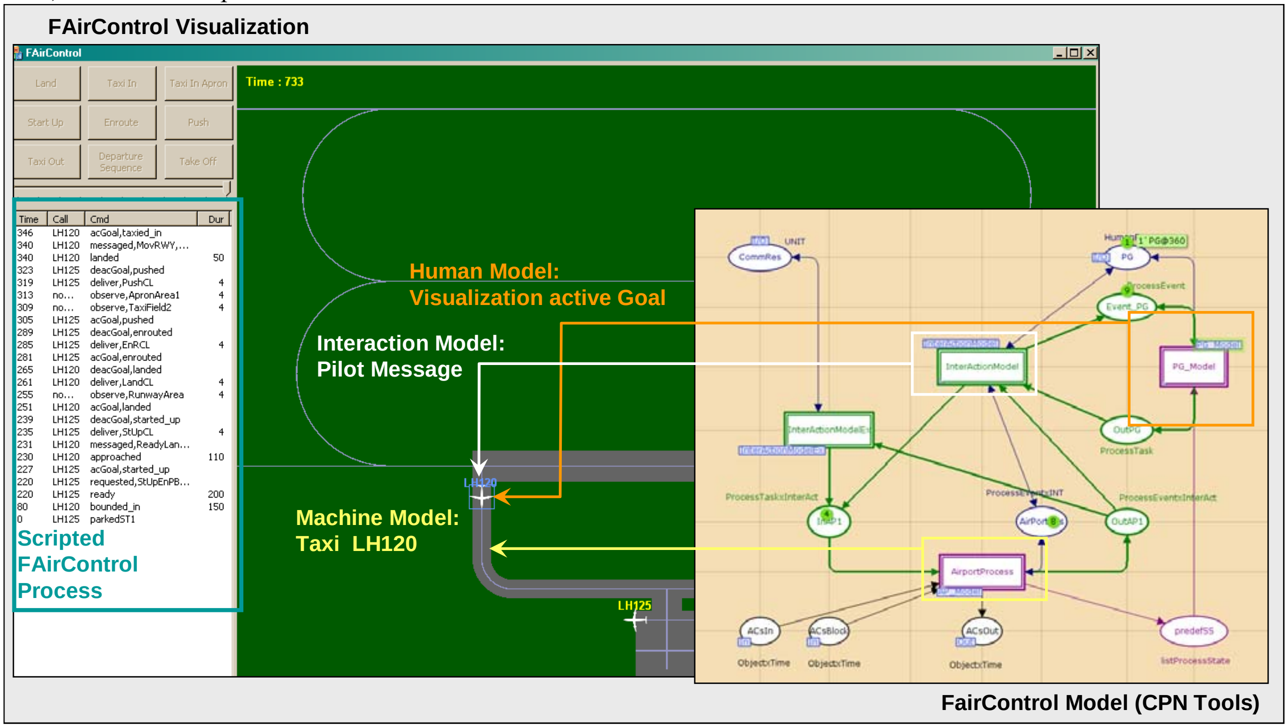

Fig. 1: Visualization of Formal Airport Control Model (FAirControl): CPN Model for simulation of interaction between human, interaction, and process model; right side), and graphical visualization of the controlled work process in a simplified airport microworld. Currently pursued goal of the human model highlighted by a blue frame (orange arrow). By changing the colour of the call sign (here: LH120) the communication with the pilot is illustrated (white arrow).

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The interaction model defines the controller-process interactions and includes sub networks for description of information resources, such as radio communication and visual perception of the traffic situation. Consequently the human model(s) and machine model(s) can work independently from each other for certain time periods. The state of the airport process model determines the type and content of visual and electronic surface traffic information (e.g. usage of taxiways, landing clearance) which can be acquired and communicated by the controller. The controller model (human model) is implemented as a Formal Cognitive Resource (FCR) Model [10] and serves for the description of controller behaviour in the tower work environment. As most important feature this model considers the motivated character of human work as related to the limitations of cognitive resources [7].

The graphically represented formal work process model as depicted in Fig. 1 supports the communication between domain experts and system developers by simulating different traffic situations during the structured interviews. A condensed result as obtained by szenario based interviews of two senior controllers, aiming at the relevance of visual information ordered by area / distance, is presented in the following list:

1. Approach-/ Departure Range (2-3 km, max. 5km)
   a. Recognition of A/C & direction of movement
2. All Airfield Areas (Taxi, Apron, Stand)
   a. Recognition of all active objects (A/C, vehicles, humans, animals)
   b. Classification of A/C
   c. Recognize Smoke at A/C
3. Runway Range (800-1500m, max. 2 km)
   a. Observe Runway state, detect aircraft parts
4. Taxi Area (500-900 m, max. 2 km)
   a. Recognition and position of passive objects (A/C and parts, vehicles, obstacles)
5. Apron Area (200m)
   a. Recognize aircraft damage
6. Stand Area
   a. Recognize Aircraft damage
   b. Recognition and position of passive objects (luggage, vehicles)
7. RWY / Taxiway Lights
   a. Monitor Intensity
   b. Monitor Function

III. Experimental Videopanorama System

Motivated by the above mentioned relevance of visual information for tower work processes, a high resolution video panorama system was set up at Brauschweig research airport as experimental environment for investigation of different aspects of the RTO HMI and development of a demonstrator [1][2]. A block diagram of the augmented vision video panorama system is depicted in Figure 2. The sensor component consists of four high resolution (1600 x 1200 pixels) high dynamic range (14 bit/pixel) CCD cameras ($P_{1,\ 2,\ 3,\ 4}$) covering the Braunschweig airport within 180° and a remotely controlled pan-tilt zoom camera (P_5: PTZ).

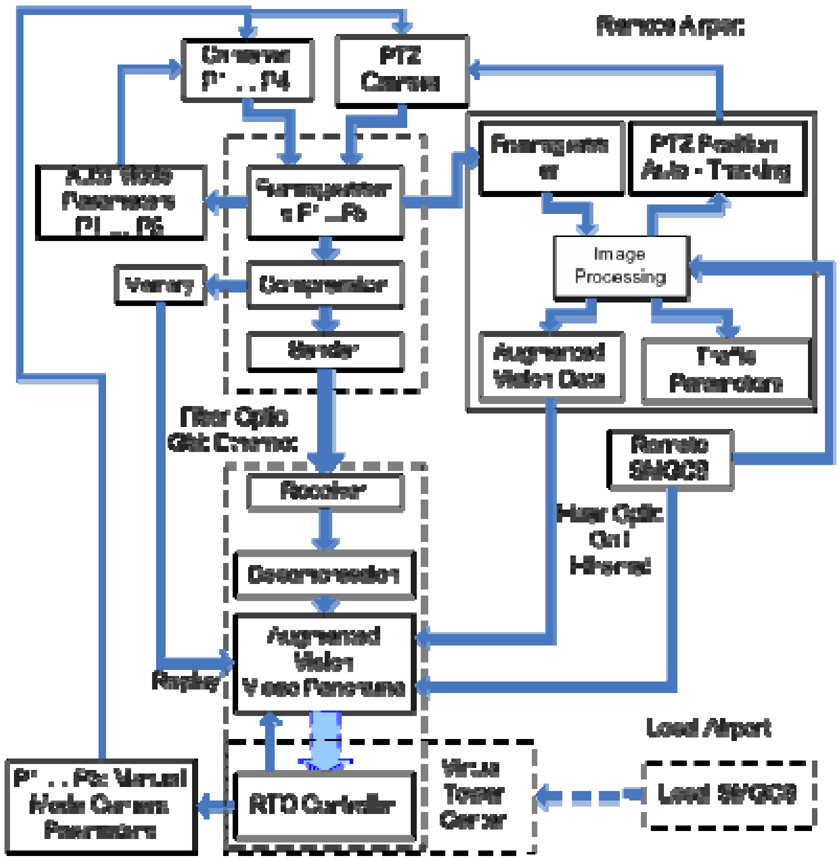

Fig. 2: Schematic block diagram of augmented vision video panorama system. Wide light arrow indicates visual information for the controller.

Figure 3 gives an aerial view of the Braunschweig research airport with fiber-optic datalink connecting multilateration sensor containers with the main control center, and indicating camera position and viewing sectors.

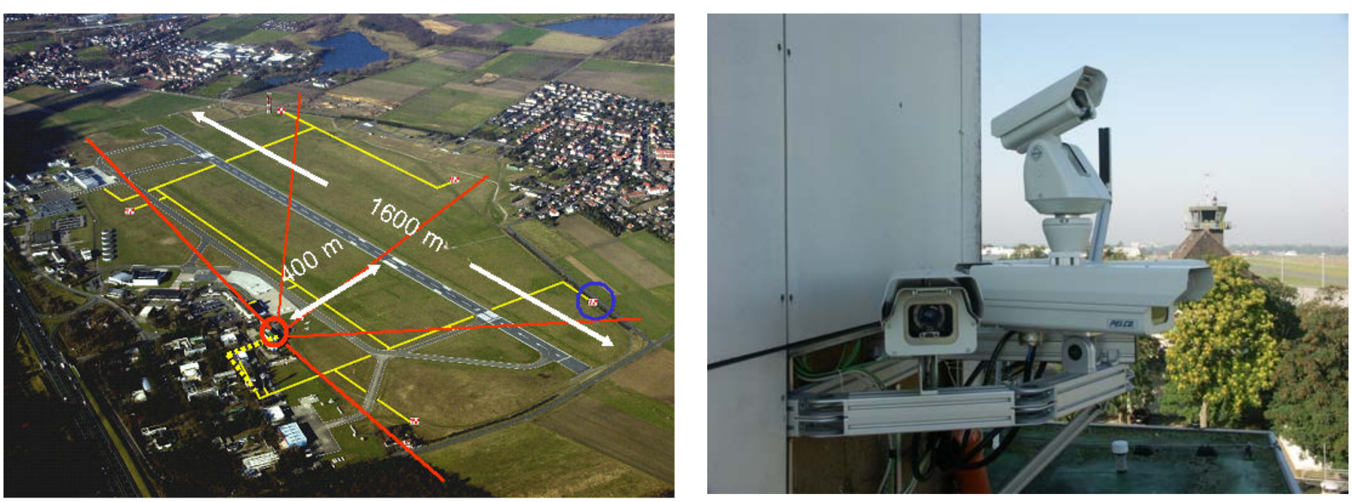

Fig. 3: Braunschweig research airport with with 1.6 km runway extending E-W, fiber optic data link (thin yellow lines) connecting sensor containers. Circle with radiating lines indicate camera position and sectors respectively. High resolution panorama camera setup and pan-tilt zoom camera of the video panorama system. Braunschweig tower in the background. Blue circle highlights container used for video resolution estimate. (Photos: DLR)

The cameras (photo at the right of Fig.3) are positioned ca. 20 m above the airport surface, horizontally aligned on top of a building at the southern boundary of the airport with 100 m distance to Braunschweig tower, 400 m south of the runway which extends in E-W direction. The vertical aperture angle of about 20° (half angle with respect to the horizontal line of sight) allows for a closest surveillance distance of about 60 m.

An optimistic estimate of the theoretically expected object resolution may be obtained by elementary optics and the given data of the electrooptical camera parameters. By using the fundamental relationship $G / B = (g/f - 1) \approx g / f$, with f = focal length = 12.5 mm, g = object distance, G = object size, B = image size, and a CCD pixel size of 7.5 µm (+ 0.5 µm gap), the vertical object size at g = 1 km distance corresponding to 1 Pixel is G / B = 0.6 m / 1 Pixel vertical, or ca. 2 arcmin angular resolution, and 1 m / 1 Pixel along the line of sight. The observable resolution at the videopanorama HMI is reduced due to imperfect optics of the camera, the dynamic (illumination dependent) image compression, and resolution of the display system. The optimistic resolution value of about 2" (two times the diffraction limited value of the human eye) may be approached with decreasing camera aperture, which is of course possible only under good light conditions and object – background contrast. This prediction was tested with known static objects on the airfield (see section 4). For realization of the panorama only 1424x1066 Pixels of each camera (50° viewing angle) are actually used in order to match the 180° panorama angle.

For each camera the signals with 25 frames/s are split into two outputs. One feeds the data compression for transmission to the remote RTO HMI, while the other drives the simultaneous real time image processing running on a parallel workstation.

A GBit ethernet switch feeds the images from the five sensors into a single mode fiber optic data link which transfers the typically 100 MBit/s data of the panorama system and PTZ over a distance of 450 m to the visualisation system. A second GBit ethernet switch splits the incoming data into five output channels for decompression with one PC per camera. Each camera is remotely controlled with respect to aperture and γ correction. The PTZ camera is controlled with respect to azimuth, vertical angle and zoom (23-fold, focal width 3.6 mm – 82.8 mm, corresponding to 54° - 2.5° visual angle).

In addition to the visual information digitized acoustic signals of a microphone and weather data (temperature, wind speed, static pressure) from a weather station at the camera position are transmitted to the RTO-HMI via the same fiber optic link.

The latest version of the Augmented Vision Videopanorama (AVP-) HMI for a single operator / single airport surveillance is shown in Fig. 4. It is based on four high resolution LCD-monitors (UXGA, 1600x1200 Pixels) for displaying the reconstructed panorama and a separate one for display of the remotely controlled PTZ-camera. Image decompression, synchronization and interfacing to the inputs of the controller is realized with a cluster of dual-core workstations, one for each display. Interaction of the operator with the panorama system (cameras, weather station, microphone) is performed via pen touch-input display for modifying lens aperture, exposure time, γ correction of cameras and PTZ control. For PTZ positioning the target can be defined manually or by automatic movement detection. A rectangular contour is positioned at the respective location of the panorama, defining the target area to be enlarged. With the tracking mode turned on the square moves coherently with the corresponding object. An algorithm for real time movement detection is running on a separate parallel processor of the image compression PC of each camera. An overall latency time between image acquisition and panorama visualization of 230 ms – 270 ms was measured by means of a special shuttered laser arrangement.

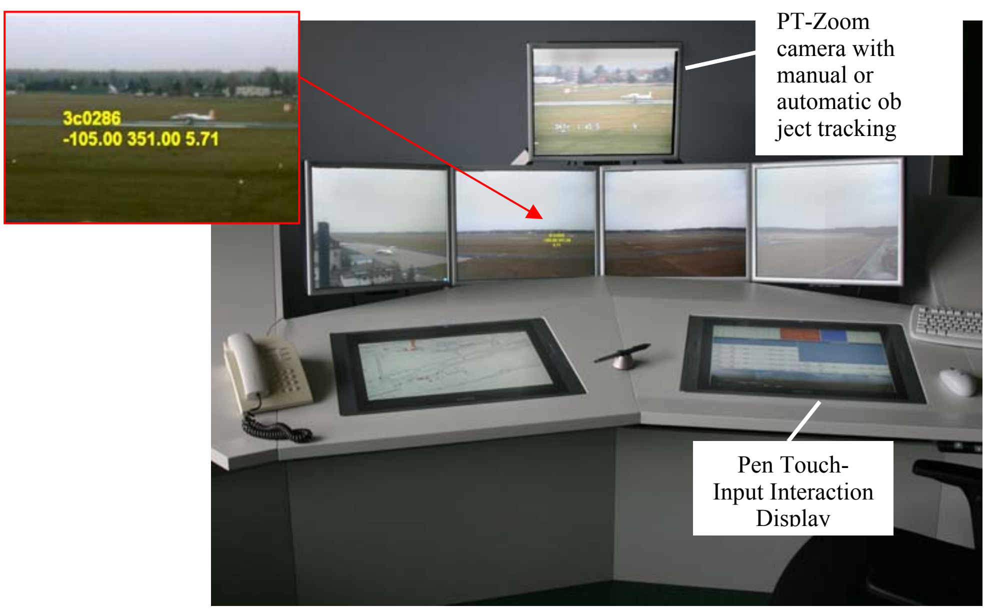

Fig. 4: RTO HMI for single operator / single airport surveillance, integrating videopanorama, PTZ display, and pen touch-input interaction display.

The pen touch-input display was designed to incorporate additional features, aside from the control of the PTZ camera, in order to obtain a compact RTO operator HMI which should fit into a typical tower environment of a medium size airport. Figure 5 exhibits details of the present design. The mini-panorama at the top is updated with 5 Hz and serves for commanding the PTZ orientation via pointing of the touch-pen. The center is occupied by flight strips (presently not connected to flight data) providing data on incoming and outgoing flights, with the possibility for handwritten notes by the controller by using the touchpen. On the left side of the electronic strips a field of keys is placed, e.g. for switching runway / taxiway lights. On the right side a control panel for optical PTZ-parameters, a virtual joystic for PTZ orientation, and a display of a weather station at the camera position can be seen.

Within the video panorama real-time aircraft position information is integrated as obtained from the multilateration system at the Braunschweig airport via the aircraft (a/c) transponder (see Figure 3). Under reduced visibility this Augmented Tower Vision (ATV) feature allows for localizing the a/c near the correct position because the transponder code, a/c label and numerical information are integrated near the nominal a/c image location in real time. Contours of the movement areas are superimposed on the reconstructed panorama for guiding the operators attention during darkness or bad weather conditions to those areas where moving vehicles are expected.

Fig. 5: RTO touch pen input display for controller system interaction, including electronic flight strips, weather data, mini panorama and virtual joystick for PTZ

One important advantage of the so called video see-through augmented vision technique using the digital video panorama is the easy integration of augmented vision features. This characteristic avoids the problem of (computational) delay between real scene and augmented information of the optical see-through technology as realized with the head–up and head mounted techniques (e.g. [8]). Initial laboratory experiments and theoretical investigations with superimposed information on the far view addressed the human performance such as response time and head down time reduction by using transparent displays for reducing the number of monitors [11][12], and the problem of spontaneous cognitive switching due to ambiguous stimuli [13].

The five recording PC's with the compression software at the camera position allow for storing panorama and zoom data (roughly 40 GByte of data per hour) and provide the possibility of complete panorama replay. Presently this feature is used for the augmented vision HMI development and validation experiments (see section 4).

IV. Initial Validation Experiments

The main question to be answered refers to the comparability of the video panorama with the real view out of the tower windows. With the known size and distances of static objects on the airfield it is possible to evaluate the practically achieved effective video panorama resolution as compared to the theoretical estimate of 2 arcmin (0.6 m / Pixel at 1 km) given in section 3. We may take the red-white multilateration sensor-containers as reference objects (see Fig.3, height and width G = 2 m). The nearest containers as captured by the NE and E-looking camera $P_{3,4}$ are located at distances g_E = 400.8 m and g_{NE} = 588 m (dark blue circle) respectively. With the lens equation of section 3 we obtain 7.8 and 5.3 pixels of the camera chip covered by the container image in the vertical direction. Evaluation of single video camera frames (cameras P3, P4) reveals 8-9 and 5-6 pixels, depending on the selected intensity threshold. The corresponding theoretical vertical display image size is 2.4 mm (ca. 9 Pixels) and 1.6 mm (6 Pixels) respectively. The size measured on the displays is 3 mm and 2.5 mm respectively, i.e. 25 – 60 % larger than predicted by elementary optics, with a correspondingly reduced value of the video resolution as compared to the theoretical 2 arcmin value. The red-white container coloring is resolved in both cases, however, as expected somewhat reduced as compared to the real view.

For initial steps towards validation of the system a flight-test plan was set up for experts and non-experts to evaluate identical scenarios under real view and video panorama conditions. Flight tests of two hour duration each, with the

DLR DO-228 (D-CODE) test aircraft were designed with successions of approach, touch-and-go (or low approach) and takeoff. On December 13 2006 the first out of four planned 2-hour trials were performed. Five subjects (2 controllers of the Braunschweig Tower (S_1,S_2), and 3 non-experts (S_3, S_4, S_5, members of the human factors department)) observed the flyby from a position near the panorama camera system and monitored times of 11 characteristic events $e_1 - e_{11}$: out of sight, low / steep dept. angle, take-off, touchdown, approach main / grass runway, landing gear down / up, steep approach, first sighting. The measurements were performed with time synchronized camera and notebook computers using a specially designed data input software. Significant time drifts of the individual notebooks were corrected for by comparing with the P_1-camera time as reference before and after the 2-hour experiment. Pilots received the flight plan for up to 16 approaches (with 11 realized). One out of the 11 recorded GPS trajectories with the onboard Omnistar satellite navigation system is shown in Fig.6, including event observation positions $x(e_i)$ of the corresponding observation times $t(e_i)$. The distance between the runway and approach turning points is 4 km and 14 km respectively. Flights were performed under VFR conditions with lower cloud boundary at 600 m. Each flyby was characterized by 6 parameters, with parameter values statistically mixed: 1. approaching main (concrete) or grass runway; 2. approach angle normal or high; 3. landing gear out: early, normal, late; 4. low level crossing of airport or touch and go; 5. touch down point early or late; 6. departure angle normal, low angle, steep angle.

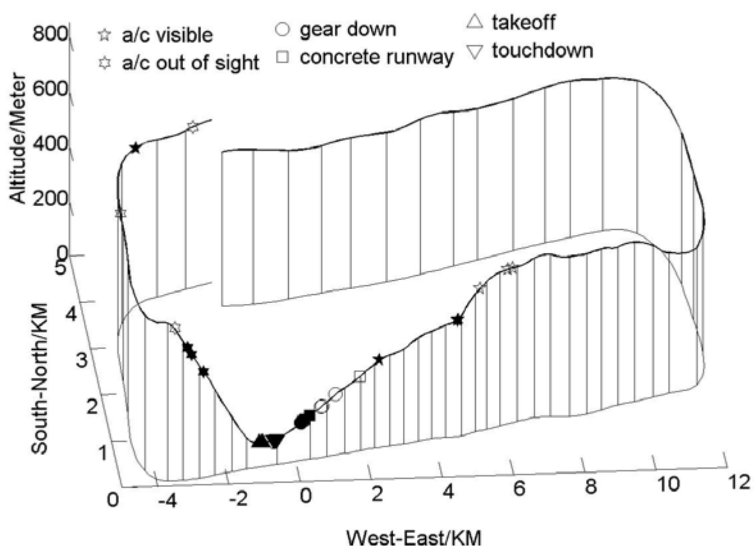

Fig. 6: GPS trajectory no. 4 out of 11 test flights of 13/12/06 (clockwise direction). Open / filled symbols represent event observation under real view / video panorama conditions.

While pilots had a detailed plan to follow for the sequence of approaches with different parameter values, the subjects only knew about the different possibilities (e.g. approach grass or main runway) within the approaches. They had to activate the corresponding field of their input display of the tablet PC and set a time mark at the time of their observation of one out of 11 possible events ($e_1 - e_{11}$) during each of the D-CODE approaches / flybys (e.g. a/c visible = first sighting of aircraft, mostly recognized by the head light under the present (weather) conditions). Also all approaches of additional (non-D-CODE) a/c were monitored. Experts and non-experts were briefed separately before the first experiment, with both groups filling separate questionaires. After the first 2-hour test raw data from all subjects and for all approaches under real view conditions were collected into a single data file. Evaluation of the different approach, touch-and-go, and departure conditions (altogether 14 approaches with 11 D-CODE and 3 other aircraft) yields the inter-subject time measurement scattering with mean and standard deviation (stdev) of the sample and standard errors (sterr) of mean for the n = 5 subjects.

Typical unbiased estimates of sample stdev for event e_{11} (first sighting during approach) are between 2 s and 25 s (sterr = 1 – 15 s). Comparing approach recognition time with low stdev with the GPS track yields first sighting of a/c (headlight) at distance 9 km. The minimum sterr of e.g. 1 s for e_{11} and 0.2 s for e_5 (touchdown) presumably represent the optimum observation conditions for all subjects (all n = 5 attending first sighting direction during expected apearance time).

Detailed information on the difference between real view and video panorama are obtained by repeating the experiments with the video panorama replay after a week or more in order for the subjects to no longer remember the different flight conditions. It was expected that due to lower resolution of the videopanorama (theoretical estimate $\alpha_V \approx 2$ arc min, see section 3) as compared to the real view, distant events of approaching /departing a/c (like first / last sighting of a/c) should receive an earlier/later mark under real view as compared to video observation. Correspondingly within-subject evaluations of the direct viewing and video panorama replay observations yields time differences t(video, e_i) – t(real view, e_i) > 0 and < 0 for approaching (app) and departing (dpt) a/c respectively. All five subjects (two controllers and three non-experts $S_{1,2,3,4,5}$) repeated the experiments with the videopanorama replay within 1&2/2007. In Table 1 the results for six of the 11 possible observation types are shown for all subjects and all flights with pairs of real view – video time marks, with mean Δt(video - real view), standard deviation and std. error of mean. All displayed events exhibit reproducible and significant pos.(dpt.) and neg.(app.) delays between video panorama and real view conditions. For example the significant positive delays measured as overall mean for e_8 (landing gear visible, 16.5 ± 2.7 s) and e_{11} (first sighting, -29.3 ± 3.5 s) show these events to be observable only 0.9 and 1.5 km respectively closer to the airport (a/c speed ca. 100 kn = 185 km/h), as compared to the real view conditions (e.g. e_{11}(real view): a/c (lights) recognized at ca. 8 km). If we assume that detection time difference is determined by the difference of optical resolution between real view (resolution of the human eye ca. $\alpha_E \approx 1$ arcmin = 1/60 °) and videopanorama system, the measured time difference Δt(video-real view) = $t_V - t_E$ can be used for calculating the effective resolution α_V of the optical system.

Table 1: Mean, standard deviation and std. error of event observation time difference t(replay) – t(real view).

Event e_i	**N**	**Mean Δt / s**	**S.D. / s**	**S.E. / s**
e_{11}: A/C visible	53	29.3	25.4	3.5
e_8: Gear visible	34	16.5	15.5	2.7
$e_{6,7}$: RWY identified	48	13.8	27.9	4.0
e_5: Touchdown	27	-0.13	1.3	0.3
e_4: Takeoff	21	0.40	1.1	0.2
e_1: A/C out of sight	42	-13.46	21.0	3.2

"Effective" α_V means that the contrast or modulation depth of the image structure is not treated separately for this initial evaluation. For suitable events with known object size the single Δt-values allow for calculation of α_V via:

$$\alpha_V = \alpha_E\left(1 - \alpha_E v_E \Delta t / G\right)^{-1} \qquad (1)$$

where the resolution angle α is given by $\alpha_{E,V} = G / x_{E,V}$, with event observation distance $x_{E,V}$ under real view (E) and video (V) conditions. G is the object size, e.g. aircraft cross section for e_{11} or landing gear wheel size for e_8. For e_{11} and e_8 we obtain in this way $\alpha_V = 1.3\ \alpha_E$ (using G = 2 m, aircraft speed v_E = 100 kn) and $a_V = 2.0\ a_E$ (with G = 0.5 m, v_E = 100 kn) respectively. While the second value is in excellent agreement with the theoretical estimate of $\alpha_V = 2\ \alpha_E$, as obtained from elementary optics, the first one is even smaller (better resolution). In order to obtain a statistically relevant and model based mean value, a linear regression procedure is employed for those events where the optical resolution (more or less modified by image contrast) may be assumed to play the dominant role for event timing. Because e_1 was unreliable due to observability problems (the aircraft quite often vanished from the P1-camera observation angle before e_1 was observable), only e4, e5, e8, e11 were used for this evaluation. For applying a regression procedure the independent variable "event e_i" has to be replaced by a quantifiable variable. A linear model is obtained when considering the observation distance x as obtained from the GPS reference trajectory instead of the observation time, yielding a Δx(video – real view) versus x_E dependence for regression analysis. Figure 7 shows the scatter plot of the four data points (x_E, $\Delta x = v_E \Delta t$), as obtained by correlating the measured time values with the corresponding GPS position data, together with the least squares fit.

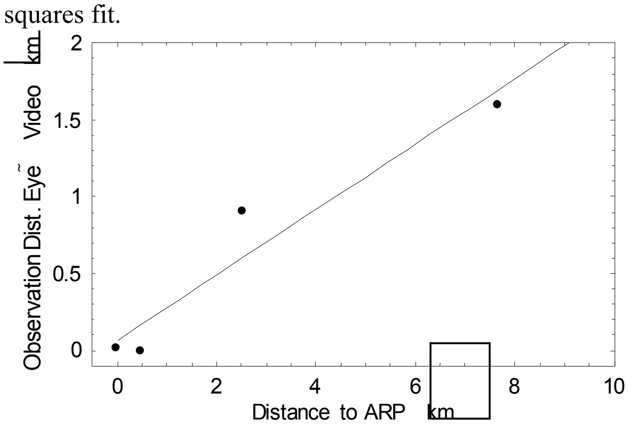

Fig. 7: Mean event-observation position differences Δx (real view – video replay) between real far view and video panorama conditions versus mean GPS-position estimate $x_{E,V}$ = distance from event position $x_{E,V}$ to airport reference point ARP.

With Δx(eye – video) = v_E Δt and x = G/α_E equation (1) yields the linear model

$$\Delta x(\text{eye} - \text{video}) = \left(1 - \alpha_E/\alpha_V\right) x_E \qquad (2)$$

or

$$\alpha_V = \alpha_E\left(1 - \beta_1\right)^{-1} \qquad (3)$$

with slope $\beta_1 = \Delta x / x_E$ estimated via a least squares fit as b_1 = 0.21 (± 0.04, std.err.). R^2 = 0.92 and significance level (F = 25.4 at p = 0.04). As expected from the fit the corresponding α_V estimate of 1.3 arcmin as based on the linear model $\Delta x(x_E)$ lies near the e_{11}-value obtained via Δt. Because for the large distance of e_{11} the image contrast (modulation transfer) may be assumed to have a larger influence on the detection threshold than for e_8, the resolution equation (1) probably is more appropriate for event observations closer to the ARP (i.e. e_8), which means that the theoretical resolution of 2 arcmin = 1/30° is verified by the field test results.

V. Conclusion and Outlook

Basic elements of DLR's experimental Remote Tower

Operation (RTO) system at the Braunschweig Research Airport are described and initial field test results reported which are evaluated by assuming the optical resolution to play the dominant role for event detection. The motivation for design of a high resolution augmented vision video panorama as basic RTO HMI is highlighted, based on work and task analyses. Important advantages as compared to the current work situation, such as zoom with tracking function, video-see-through augmented tower vision (ATV) for improving low visibility conditions, and panorama replay are presented. Quantitative evaluation of initial field tests for comparing real view and video panorama observation verifies the theoretically predicted video resolution of 2 arcmin. This reduced resolution as compared to the human eye (1 arcmin) may be compensated by the mentioned advantages of the technical system. The RTO HMI will be integrated into the DLR tower simulator environment, allowing for simulation of different work scenarios, e.g. simultaneous control of two airports. Detailed evaluation of simulator and work model based RTO simulations and additional field tests will provide design guidelines for the RTO prototype which includes the additional voice communication and flight data systems required for operational tests within a shadow mode environment.

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Space Plus Time Investigations: a 3D Air Situation Display to Support Controllers in Approach and Tower Sectors

Antonio Monteleone, Luigi Mazzucchelli and Antonio Nuzzo

Abstract— **The AD4 project has focused its investigations and technological developments on building an innovative Virtual Air-Space representation for ATM system. This paper presents the most relevant results of the evaluations of the 3D/4D APPROACH and TOWER HMIs (Human Machine Interfaces) developed in the context of the project activities and conducted to establish the "fitness-for-purpose" of the AD4 Operational Concept.**

***Index Terms*— 3D Radar Display, 2D-3D integration, ATM, Approach Control, Control Tower, Situational Awareness, Augmented Reality**

I. Introduction

THE **AD4** project [1] [2] [3] [4] has focused its investigations and technological developments on building an innovative Virtual Air-Space representation for ATM system.

The Operational Concepts explored by AD4 consisted in deploying 3D/4D (**Space plus Time**) HMIs to enhance the presentation of spatial-temporal information necessary for controller's job. In particular, the AD4 project has developed a novel **3D Air Situation Display** (3D radar picture) based on the representation of visual elements within a purely synthetic 3D Virtual Environment. Such virtual environment provides a 3D perspective display of the traffic managed within an ATC sector. The 3D situation display sits on top of a scalable, robust and secure middleware based **IT platform** (a fully operational test-bed) that allows interoperability and usability in real and simulation ATM environments (e.g. ESCAPE/ACE and ATRES). Such integrated environment has been successfully used to evaluate the most relevant 4D HMI concepts and representations by **Real-Time Human-in-the-loop Simulations** with the involvement of controllers and simulation of the operational ATC environment.

Therefore, **interoperability with external systems** has been a targeted objective of the projects, achieved by the supports of standard exchange formats (e.g. **ASTERIX**) and CORBA IDL interfaces for the ATC domain (e.g. **AVENUE** and **ACE**)

This work presents an overall assessment of the results of the evaluations of the 3D/4D **APPROACH** and **TOWER** HMIs (Human Machine Interfaces) developed in the framework of the AD4 project and conducted to establish the "fitness-for-purpose" of the AD4 Operational Concept [5].

Following **MAEVA** methodology, high level evaluation objectives were identified and mapped to a set of low level objectives with associated hypothesis, metrics and data collection methods.

Two separate validation sessions were conducted:

- Execution of Demonstrators Test with Human in the Loop simulations for the APPROACH 4DHMI[1].
- Execution of Demonstrators Test with Human in the Loop simulations for the AIRPORT 4DHMI[2].

Furthermore, trials on **Augmented Reality** technology were performed in the Airport Tower of Naples: real ATC traffic on airport surface was augmented with surveillance data (e.g. call-sign, speed, etc.) and presented to controllers during sessions conducted on the 22nd and 23rd of February 2007 in the control tower [5] [6].

Based on the results of the validation sessions, this paper outlines some general considerations on the use of 3D HMIs in Air Traffic Control environment, highlighting advantages and drawbacks. Strategies to mitigate the identified drawbacks are suggested and future research activities are thus forwarded.

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[1] The evaluation for the APPROACH 4DHMI took place with support of ENAV and SICTA at the Airport of Naples from 25th to 27th November 2006. Four active air traffic controllers from the Naples Approach Sector and human factors experts were involved in the simulations and evaluations of the system.

[2] The validation for the AIRPORT 4DHMI took place at SICTA premises in Naples the 24th and 25th January 2007. In that occasion, four experienced air traffic controllers played an active role within three simulated scenarios during a human in the loop simulation.

II. The AD4 Project

The AD4 project has focused its investigations and technological developments on building an innovative Virtual Air-Space representation for ATM system, providing a range of valuable benefits to support efficient control systems where 3D real time interaction with air traffic/airport space is accessible to the controllers.

The AD4 project has addressed this objective though

- the analysis of Operational Concepts and Human Factors
- the engineering of the IT infrastructure and its core Components (4D HMIs, Middleware, Predictive and Applicative Components, Interfaces to external data e.g. Meteo and ATM system integration)
- the development of the working Demonstrator for an operational context
- the validation by the use of the MAEVA methodology and the assessment and exploitation of results.

A. The AD4 3D Air Situation Display

The AD4 project has developed a novel **3D Air Situation Display** (3D radar picture) based on the representation of visual elements within a purely synthetic 3D Virtual Environment. Such virtual environment provides a 3D perspective display of the traffic managed within an ATC sector. The 3D situation display sits on top of a scalable, robust and secure middleware based IT platform that allows interoperability and usability in real and simulation ATM environments.

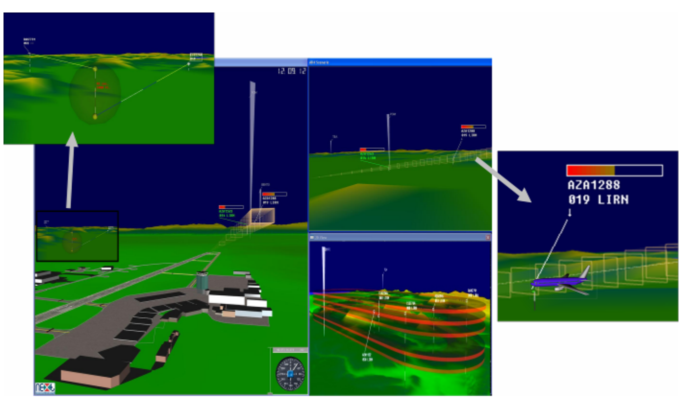

Fig. 1. AD4 3D Radar Display overview.

The AD4 system provides a 3D Display of the controlled environment, including **3D representation of constraints** (terrain, radar minima, military restricted airspaces, clouds) and aerodromes. 3D representation of **waypoints** and **airways**, **holding stacks**, **ILS paths** are supported in order to provide controllers with a clear reconstruction of airspace.

Display capabilities of the AD4 system can be summarized in the following list:

1) 3D Display of the controlled environment (Airspace, particularly the Approach phase, and Airport environment) including constraints (terrain, radar minima, military restricted airspaces, clouds)
2) 3D Display of visual elements aimed to improve controllers situation awareness in the APPROACH sector:
   - **Aircraft trajectories intersection** with vertical and temporal separation at the intersection point;
   - **Holding stack** nominal volume, presence of aircraft in the stack (holding stack flight levels occupancy) and foreseen time to exit from the holding circuit;
   - **Intersection** between aircraft trajectories (both real and hypothetical) and **military restricted** airspaces. Time to the intersection point is displayed as well;
   - **Hypothetical trajectories** (what_if trajectories);
   - Intersection of hypothetical and real aircraft trajectories with vertical and temporal separation at the intersection point;
   - Relative position of aircraft trajectory against **ILS** volume;
3) 3D Display of visual elements aimed to improve controllers situation awareness in the Airport environment:
   - **Taxiways** and **runways**, represented in different colours to show different states (e.g. free, engaged);
   - **3D gates** located along runways and landing paths, to show the position of critical points (points of no return) for landing and take off manoeuvres;
   - Relevant 3D **buildings** and **parking areas** (apron);
   - 3D shape of aircraft, represented by a simplified geometric model, but with real size of actual aircraft;
   - Identification **labels**, associated to each aircraft and providing the relevant data such as the aircraft type, the call-sign, and other auxiliary information;
   - A vertical segment (or an arrow) representing **aircraft acceleration** and an horizontal one representing stopping distance;
   - Aircraft **projected volume** to show the foreseen occupied volume along the expected direction of motion, in a given time;
   - Visual alerting mechanisms to display different sorts of **runway incursions**.

B. Evaluation and Assessment: the AD4 test bed

A series of experimental activities were conducted to assess and demonstrate the entire portfolio of results achieved by the AD4 project to controllers and technical specialists.

The AD4 Operational Concepts consisted in deploying 4D (Space plus Time) displays in order to enhance the presentation of the spatial-temporal information necessary for controller's job.

Following MAEVA methodology, high level evaluation objectives have been identified and mapped to a set of low level objectives with associated hypothesis, metrics and data collection methods. In particular safety (mapped to both workload and situation awareness low level objectives), usability and acceptability have been identified as high level objectives of the AD4 evaluation activities.

Real-time simulation, with the involvement of Air Traffic Controllers, has been selected as the most appropriate validation technique and ATC simulation platforms, like Eurocontrol ESCAPE/ACE and Vitrociset ATRES, have been chosen as real time ATC simulators to feed the system with simulated operational data (i.e. radar tracks, flight plans) and events (i.e. conflicts) in both APP and TWR sectors.

A **Test-Bed to experiment with and validate the use of 3D/4D displays** in the ATM domain has been so developed by the integration with the above mentioned simulation platforms in the ATC domain. Such integrated environment has been successfully used to evaluate the most relevant 4D HMI concepts and representations by Real-Time Human-in-the-loop Simulations with the involvement of controllers and simulation of the operational ATC environment. **Interoperability with external systems** has been a targetted objective of the projects, achieved by the supports of standard exchange formats (e.g. **ASTERIX**) and CORBA IDL interfaces for the ATC domain (e.g. **AVENUE** and **ACE**).

III. RTHLS[3] IN THE APPROACH SECTOR

The APPROACH validation session [5] was aimed at evaluating the use of a 3D interface for the Approach Control with particular attention to investigate on the following topics:

1) whether and why 3D is valuable for approach controllers;
2) implication of 3D on situational awareness;
3) 3D HMI difficulties and usability issues from approach controllers;
4) Acceptability of the 3D system from active controllers.

The evaluation for the APPROACH 4DHMI took place at SICTA simulation room at the Airport of Naples from 25th to 27th November 2006 [10]. Four experienced ENAV air traffic controllers from the Naples Approach Sector were recruited to play an active role in human in the loop simulations.

The experiment aimed at evaluating the AD4 operational concept in a simulated working environment that was a replica of Naples Approach Sector.

The goal was to get evidence of the potential impact of the innovative 3D HMIs on controllers work. Issues related to 3D air traffic representation were so investigated by three high level validation objectives: safety, usability and acceptability. Furthermore Situation Awareness and Workload were chosen as safety related indicators.

During the Real Time Human-in-the-loop Simulation sessions the controllers were able to assign instructions and clearance to aircraft, being in contact with pseudo pilots as well as controllers of other sectors.

Each simulation run lasted about 30 minutes and referred to one of three selected scenarios such as the **management of vertical separation**, the **monitoring of holding stack** and the **monitoring of final approach path**. HMI presented to controllers consisted of a 3D display placed side by side to a standard Controller Working Position (CWP). Controller/pilot and controller/controller communications were conducted using the standard CWP.

Fig.2. The experimental working position in operation, with the executive sitting on the left, and the planner on the right.

A real traffic sample was adapted to each selected simulated scenario: management of vertical separation, holding stack, final approach fix.

The platform used for evaluating the AD4 Operational Concepts derived from the integration of the AD4 3D radar display with the Eurocontrol ESCAPE-ACE (Avenue Compliant ESCAPE) simulation platform.

Post-run interviews and questionnaires were used to collect data about the experiment and get a qualitative understanding of the potential impact of 3D displays on air traffic control. In particular interview guides were used to get feedback on situation awareness (intended as a safety indicator) and usability, while CARS (Controller Acceptance Rating Scale) was used to measure acceptability.

A. Results

1) Situation awareness

In order to investigate the impact on safety of the innovative 3D HMIs, one of the questions addressed by the experiments referred to the capability of improving controllers situation awareness by the use of 3D HMIs.

To find an answer to this question controllers were asked to rate their overall situation awareness during each simulation run. The answers to this query indicated a “good” or “quite good” rating in the judgment of the perceived situation awareness.

This good result was basically due to the display configuration adopted for the experiment (side-by-side 2D and 3D displays). In fact during the experiment controllers spent more time looking at the familiar 2D radar display than at the innovative 3D display; 3D was mainly used to verify the

[3] Real Time Human in the Loop Simulation

results of their actions (clearances) and to anticipate possible problems arising from deviation from assigned paths rather than monitoring the overall traffic situation [5]. In other words the 3D display was mainly used to focus on specific situations previously identified in the 2D radar display.

If one distinguishes between global and local situation awareness, the analysis of the experiment indicates that use of 3D helped in improving controllers local situation awareness, while presence of the 2D display allowed them to keep a good global situation awareness.

This result is not surprising if one considers that 3D perspective displays provide a view of the area of interest as seen from the 3D camera position and that 3D perspective representations suffer of the so-called perspective distortion and occlusion problems. Perspective distortion is an intrinsic characteristic of perspective transformations that renders not always easy to judge relative distance among objects. Occlusion is another intrinsic characteristic of 3D representations according to which near objects are placed in front of (and occlude) far objects along the line of sight.

All these problems, intrinsic in 3D representations, can force a user to navigate within the 3D world to find the best view-point from where to observe the scene.

When focusing on limited regions of space, i.e. when drawing attention to specific situations, the effects of perspective distortions and occlusions are greatly reduced and it is possible to get fully advantage of the availability of vertical displacement of aircraft in the airspace.

Post-run interviews gave evidence to the fact that most controllers build their own 3D mental image of the controlled airspace. It emerged that controllers tend to mentally place themselves at specific points of view and look at limited portions of the airspace from there. 3D HMI for air traffic control could emulate such natural inclination of controllers. This suggests an HMI where it is possible to rapidly choose a desired 3D point of view and focus from there on specific situations (in the 3D display) in order to get awareness of what is happening locally. This view-point selection mechanism (a sort of rapid zooming technique) was implemented and explored in the AD4 Radar Display but some usability issues (mainly lack of coordination between 2D and 3D views as delineated in the following section) didn't allow its full exploitation during the evaluation experiments.

2) Usability

The evaluation of usability focused on the ease of use of the displayed information. Data concerning the ease of use of the novel design were collected by mean of interviews done at the end of each simulation run.

Many usability issues resulted from the execution of the experiment. The most interesting ones refer to

- side by side display configuration
- 3D camera view-point and navigation

HMI configuration adopted for the experiment consisted of a 3D display placed side by side to a standard Controller Working Position (CWP). The two displays presented to controllers the same airspace and traffic evolution but respectively in a 3D and 2D manner. The two displays were not coordinated, in the sense that it was not possible to act on the 2D radar display of the CWP in order to change the portion of airspace shown in the AD4 3D radar display.

Not coordinated side by side 3D-2D display configuration was adopted for its simplicity. Furthermore it constituted the most straight forward way of adding 3D capabilities to pre-existing controller working positions. Taking the two interfaces separated was also considered as a clear way of separating concerns between the two different displays, with the 2D radar display providing a global picture of the traffic and the 3D display providing more insights on specific situation occurring during the run.

During the experiment it was observed that the provided side by side display configuration caused the controllers to perform an extra-effort in switching from one display to the other one and vice-versa. In particular it caused controllers to spend an extra-time on matching the information displayed in the 2D display (CWP) with that available on the 3D one. Lack of coordination between the two displays strongly contributed to controllers perception of loosing more time than necessary in switching their attention from 2D to 3D and vice-versa.

This observation was confirmed by the feedback collected during post-run interviews where controllers asserted to have spent a considerable time in matching elements in the two views.

The experiment has highlighted that the naïve approach in integrating 2D and 3D radar displays, consisting in a side by side display configuration without any kind of coordination between them, introduces potential problems and extra-efforts in switching and matching elements in the two views.

Some countermeasures can be introduced to reduce at minimum these problems. In particular a stronger coordination and integration between the 2D and 3D views must be explored to get the best from these two different views.

Another usability issue that emerged during the experiment refers to 3D camera navigation and point of view selection.

3D camera navigation consists in the capability of changing camera placement and orientation in order to vary point of view. In general terms 3D camera navigation provides an added value to 3D representations since it allows to freely explore the represented 3D world. However 3D camera navigation can be a time consuming task, not affordable by controllers in situations of high pressure.

The experiment highlighted that free 3D camera navigation alone (birds eye navigation) doesn't completely fit controllers need.

Straight-forward techniques for rapid selection of desired camera point of view are so needed.

Some of these techniques have been implemented in the AD4 3D radar display just to overcome difficulties related to free 3D camera navigation. One of these techniques (map-based

3D navigation) is based on the use of simple mouse click and drag gesture on a top plan view of the sector (map) in order to select the desired camera point of view.

Technological constraints and the limited time-frame of the project prevented the AD4 Consortium from implementing selection of camera view-point directly on the main 2D radar display being part of the CWP. So an additional navigation display was provided.

During the experiment controllers were interested in pointing the camera view in specific positions of the airfields that they found valuable to monitor how traffic was implementing the assigned maneuvers in different part of the airspace, e.g. localizer, holding stack. To do this they used the AD4 additional navigation display

However it emerged from the experiment the need of implementing selection of camera point of view directly on the main 2D radar display, thus providing a stronger integration and coordination between the two displays.

IV. RTHLS IN THE AIRPORT SECTOR

The AIRPORT validation session [5] was aimed at evaluating the use of a 3D interface in the Tower Environment with particular attention to investigate on the following topics:

1) whether and why 3D is valuable for tower controllers
2) implication of 3D on situational awareness;
3) difficulties and usability issues coming from the use of a 3D HMI from tower controllers
4) acceptability of the 3D system from operative controllers in the control tower

The evaluation of the 3D/4D tower HMI took place at SICTA premises in Naples the 24th and 25th January 2007. In that occasion, four active ENAV air traffic controllers played an active role in a human in the loop simulation with three simulated scenarios.

The evaluation was conducted by mean of a Real Time Human-in-the-loop Simulation where controllers could assign instructions and clearance to aircraft, being in contact with pseudo pilots.

Each simulation run lasted about 30 minutes and referred to one of three selected scenarios:

1) Single Runway Incursion (an unauthorized aircraft entered the runway)
2) Double runway Incursion (two aircraft entered the runway at opposite ends, due to misunderstanding of take off clearance)
3) Loss of separation between arriving and departing aircraft (an aircraft aligned and ready to take-off could not move due to a broken undercarriage while incoming traffic had been cleared to land).

HMI presented to controllers consisted of the AD4 3D radar display with 3D representation of traffic in the airdrome area. Traffic evolving in Naples Capodichino airdrome was presented in a 3D/4D manner by such a display, allowing for visual representation of traffic disposition in both the airdrome and final landing phase. Conflict alarms, such as runway incursions, were presented as well.

Voice communication, with proper operational phraseology, was used to communicate between the tower/ground controller placed in front of the AD4 3D display and the ground-pilot placed in front of the pseudo-pilot position.

Traffic samples designed for validation exercises were based on typical traffic at Naples Capodichino airport. It corresponded to realistic ground traffic, designed in order to perform exercises respectfully of the selected scenarios. All the traffic samples were constructed to collect twenty minutes of significant data.

The platform used for the evaluation derived from the integration of the AD4 3D radar display with the Vitrociset ATRES simulation platform.

Post-run interviews and questionnaires were used to collect data about the experiment and get a qualitative understanding of the potential impact of 3D displays on airdrome traffic control. In particular SASHA (Situation Awareness for SHAPE), EUROCONTROL's questionnaire for self-assessment of situational awareness (intended as a safety indicator), was completed by the controllers after each run. Additional interview guides were used to get feedback on situation awareness and usability, while CARS (Controller Acceptance Rating Scale) was used to measure acceptability.

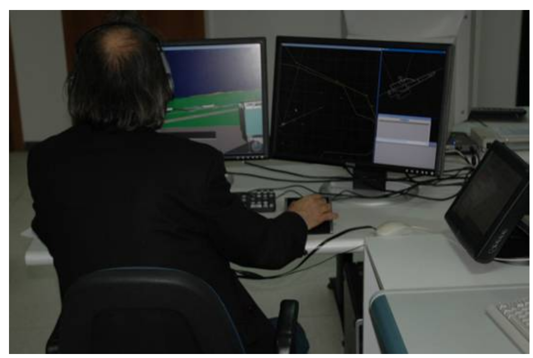

Fig.3. The Simulated working position in operation.

A. Results

Experiments conducted in the framework of the AD4 project to evaluate the impact of 4DHMIs in the AIRPORT environment indicate that 3D is potentially able to provide some added benefits compared to the resources available in current tower operational environment (the tower window, the 2D approach radar display, and the 2D ground radar display).

HMI configuration adopted for the experiment consisted of a 3D display placed side by side an additional 2D radar view display (part of the AD4 3D radar system).

During the experiment controllers behaved similarly to how they behave in the operational tower environment: 2D radar was used to manage approaching and departing air aircraft, while 3D display was used in controlling airport traffic in substitution of the tower window.

1) Situation awareness

Controllers reported that the 3D display offered a global view of the traffic, more informative with respect to the actual view available out of the window.

More precisely 3D display was used to

- Check runway status.

  3D view provided controllers with an immediate representation of runway situation and the relative access points, such as holding bays and connections. So detecting whether the runway was free and predicting future movements, such as possible incursions, required less visual effort than scanning the real world out of the window, since information about traffics position relative to the runway was entirely conveyed by the 3D display;

- Control runways ends:

  Controllers reported that 3D display provided them with an improved clarity in monitoring runway ends.

  In real world, runway ends are distant from the tower. This fact, together with weather and lighting conditions, makes difficult the discrimination of aircraft information - e.g., aircraft size, aircraft name and aircraft relative position – at the holding bays.

  Besides this improved clarity, 3D helped in lessening the visual effort to oversee the runways, because it reduced consistently the travelled distance between one end and the other which appear within a single display.

- Control distance between aircraft and to touch down.

  During the final approach controllers looked at traffic in order to evaluate distance to touch down.

- Verify the position of hidden traffics.

  Several areas of the airport are hidden, underlying factors are:

  - occluding volumes, such as building or other traffics
  - structural elements internal to the tower
  - elements out of the tower field of vision, for example traffics circulating in near the tower might not be visible from the tower controllers working position

Respect to the resources available in current tower operational environment 3D provided an integrated view of the aerodrome, which allows supervising all traffic movements, and locally inspecting some of them if needed. In fact from the experiments it emerged that

- 3D display makes available a global view of the runway without the need of a 180 degrees visual scan of the runway through the tower window;
- It allows to enrich the view with synthetic elements (i.e. labels) displaying surveillance information, conflict alerts, distance to touch down, etc;
- It emulates visual scan out of the window (head rotation) with 3D camera navigation. This point can be better appreciated considering that the view out of the window involves an estimated travelling distance of up to 180 degrees, while the "new" travelled distance is arguably contained in a few tens of degree;
- It offers the possibility of viewing also occluded portions of the aerodrome and is able to overcome visibility problems in presence of bad weather conditions and lighting.

In general, 3D emerged to provide more accurate information also than the tower video cameras. Video-camera view from the tower looking at runway ends suffers in fact from the same ambiguity problems as human view out of the tower window.

V. Experiments for the Augmented Reality in the Control Tower

This section reports on trials on Augmented Reality (AR) technology performed in Naples in the framework of the AD4 project. On that occasion real ATC traffic on airport surface was augmented with surveillance data (e.g. call-sign, speed, etc.) and presented to controllers during sessions conducted on the 22nd and 23rd of February 2007 in Naples control tower [5].

The experiment aimed at getting preliminary feedback from controllers about the use of AR visualization in the Tower Environment, with particular attention to investigate on the following topics:

- whether and why AR is valuable for tower controllers
- acceptability of an AR-based system from operational personal

A simplified AR system, based on the use of video cameras placed at fixed positions in the airport and standard monitors, was used [6].

Two active air traffic controllers from Naples Tower Control participated in the experiment. Controllers were only asked to observe the AR system in action and express their considerations on it; therefore, no direct interaction with the system was required from controllers. The ability to provide identification labels linked to the real airplanes/vehicles as well as additional information related to selected aircraft (e.g. speed, direction, etc.) was shown during the experiment.

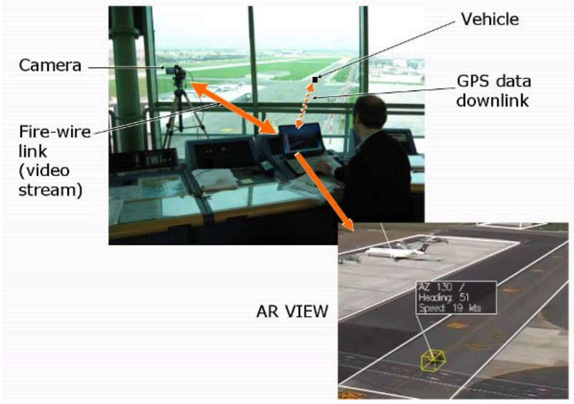

Fig.4. AD4 AR system in action

The AR AD4 system consisted of the following hardware components:

1) an AR workstation, consisting in a laptop PC, showing the AR HMI visualization window as well as other GUI control panels for the control of the visual settings and the running system;
2) a Digital Video Camera installed at a fixed position inside the control tower, looking at R24 threshold (North-East direction) through the tower windows; the camera was connected to the AR workstation via a Firewire connection cable;
3) an experimental vehicle authorized to run on the airdrome surface, according to instructions provided by the ground and tower controllers;
4) an EGNOS-enabled GPS receiver installed onboard the experimental vehicle, used for position, heading and speed tracking;
5) a wireless + ADSL network connection from the GPS receiver to the AR workstation.

A. Results

The AR HMI was overall positively evaluated by controllers and considered well acceptable. Augmented Reality was positively judged by controllers as it provided more information compared to the normal (non-augmented) “out-of-the-window” view . In particular, the following benefits were outlined by controllers:

- easier identification of aircraft/vehicles moving on the airport surface, thanks to the accompanying labels that move together with the airplanes they refer to;
- easier understanding of position of aircraft in all parts of the airport, regardless of occlusion or other visibility factors;
- easier understanding of aircraft motion (including direction and speed), especially for aircraft in very far areas (e.g. at the holding bay), thanks to the moving labels.

However, controllers raised some questions about the fact that the augmented view was showed on a standard PC monitor, rather than on other means (e.g. see-through glasses), with the following considerations:

1) the standard monitor, with images taken from a fixed camera, has the advantage of being totally not intrusive in the control tower environment, and as such it does not cause any major problems against existing procedure
2) on the other hand, the need for switching attention from the outside view (tower windows) to the AR screen was seen as a factor somehow diminishing the potential benefits of the AR technology, i.e. the ability to provide information in a single, integrated view
3) a larger screen, also combined with higher resolution camera, would make the monitor-based AR technology more acceptable (since the small screen requires the controller to stand at close distance from the screen)
4) the use of multiple cameras, and a corresponding multi-tile panoramic view, showing the whole airport surface would have added a further improvement to the effectiveness of the AR HMI (since the single camera only allows seeing a limited portion of the airport).

VI. Conclusion and Future Work

Evaluations conducted in the framework of the AD4 project indicate that 3D is potentially able to improve controller’s local situation awareness, that is awareness on specific situations involving a limited portion of the airspace (i.e. disposal of aircraft within an holding stack, position of aircraft respect to the ILS axis, monitoring of aircraft vertical separation etc.). Compared with 2D, controllers reported an increased awareness of aircraft direction, changes in the vertical speed, vertical position, and turn rate [5].

On the opposite site classical 2D radar displays provide an overall picture of traffic in the sector ensuring in this way an optimal global situation awareness not guaranteed by 3D displays. Such considerations suggest to further explore the integration of 3D and 2D displays by the construction and evaluation of so-called “ATC 2D-3D combination displays”.

2D-3D combination displays are those that present the viewer both a 2D and a 3D image of the same object in the same field of view. These displays are so intended to support typical visual perception tasks in air traffic control while providing simultaneous 2D and 3D views of the same traffic [7]. This is an emerging research theme in the use of 3D HMIs for Air Traffic Control. Researches on combination displays have been started in the course of the AD4 project with the development of several proves of concept (3D bubble, PIP and Distortion Lens) [8] to get preliminary feedback from controllers on this concept and justify further research in the field[4]. The experience gained in AD4, together with a careful analysis of the problems above, suggests that “Multiview 2D/3D” and Exo-Vis display formats are the most interesting ones and merit to be further explored[5]. Such exploration will

[4] This concept is currently subject of investigation and development in the “3D-in-2D Planar View Display” INO-CARE Eurocontrol funded project [9].

[5] In Multiview 2D/3D displays 2D and 3D are separate views that however appear in the same display.

consist in the implementation of proper 3D views within the classical 2D radar display and its subsequent evaluation with active controllers. Validation activities will make use of the platform developed in the framework of the AD4 project (i.e. the **integrated AD4-ACE platform**).

Additionally:

- Experiments conducted in the framework of the AD4 project, to evaluate the impact of 4DHMIs in the AIRPORT environment, indicate that 3D is potentially able to provide some added benefits compared to the resources available in current tower operational environment. In fact, 3D displays are able to reproduce tower scenarios by adding synthetic information (i.e. identification labels, distance to touch down, visual alerts to, etc.) to it. Such information is clearly not available by looking through the tower window. Navigation capabilities, made possible by 3D representation of the airport environment, allow overcoming visibility and occlusion problems. In other words 3D displays are potentially able to provide a novel *"all-in-one" visualization approach of the airport environment*.

- Effectiveness of 3D displays compared to last generation SWPs (Surface Working Positions) should be investigated. SWPs are able to provide a 2D detailed representation of the airdrome coupled with surveillance information and runway incursion alerts. The AD4 project did not address this issue and so it was not possible to conduct comparative evaluations between 3D and 2D SWP displays in the tower environment, not even at a qualitative level. Such comparative evaluations are however needed to confirm or go against the encouraging results of the evaluation of 4DHMIs in the AIRPORT environment.

- Exploration of the relationships of 4DHMI displays with the (Staffed) Virtual Tower Concept. Virtual Towers are ground-level facilities that are remotely located from the airport(s) to which they provide arrival/departure and ground movement services. In Staffed Virtual Towers controllers have no direct window view from the tower cab. Displays that simulate or substitute the tower window are so needed and AD4 4DHMI seems to be suitable for being used in this context.

- Early feedback from controllers on AR has been positive, confirming the initial idea about usefulness of Augmented Reality in airport environment, especially in case of low visibility, occlusions and visual identification of vehicles. Future improvements of technologies and concepts related to the application of AR technologies seem to be advisable. Dedicated efforts will be reserved to the integration of the AD4 AR visualization sub-system with advanced airdrome surveillance technologies like the ones provided by A-SMGCS systems. Investigation of the use of more sophisticated visualization displays like Head-up displays placed in front of the tower window will be investigated as well.

Also Exo-Vis displays combine 2D and 3D in the same display but in this case a central main context 2D view is surrounded by some set of detail views aimed at showing specific elements [7].

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The authors wish to acknowledge the work of all the AD4 Consortium partners that with their efforts allowed to get the results presented in this paper and more in general a better understanding of possible impacts of 3D/4D HMIs in the ATM domain. The authors also wish to acknowledge Middlesex University (United Kingdom) and Space Application Services (Belgium) for their work in the framework of the "3D in 2D Planar Display" CARE INO III project.

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A GRASP Heuristic for Scheduling De-icing Trucks at Stockholm Arlanda Airport

Anna Norin, Tobias Andersson, Peter Värbrand and Di Yuan

***Abstract*— It is a fact that the most delays in the Air Transportation System (ATS) today occur on the airport. One reason for this is the large number of actors operating at the airport and the scarcity of communication between them and other parts of the ATS. Airport Logistics is a concept developed to survey all the flows of vehicles, people, material and information, which can be found on and around the airport. The objective is to increase efficiency, where one part is to decrease the delays. As an initial step, the turn-around process is analysed and an optimization model for the planning of de-icing trucks is implemented. The model shows that large savings can be made both by reducing the travelling distances for the trucks and reducing the delays the de-icing process is causing the ATS. However, most important is the advantage of having a plan for how the de-icing trucks should be utilized, something that is missing today.**

***Index Terms*— Air Traffic Management, Airport Logistics, GRASP, Optimization, Resource Management and Simulation.**

I. Introduction

THE White Paper "European transport policy for 2010: time to decide", published by the European Commission in September 2001 [1], acknowledges the future importance of the air transport sector. This includes meeting the increasing air traffic demand and, at a higher level, supporting the continuation of the economic development of the union. At the same time, the challenges which have to be dealt with are highlighted, specifying the inevitable requirements from the society – including safety, congestion, efficiency, noise and environmental concerns.

Horizontal to these challenges, is the utilization of the aviation infrastructure, i.e. the amount of "resources" that are available supporting the air traffic service. Resources in this perspective range from airspace and runway capacity to available gates, baggage system, fuel and food vehicles and all other infrastructure, equipment and staff needed to make the air transportation system (ATS) run properly. When the air traffic grows – it is expected to double by 2020 – the airports will most likely be the bottlenecks in the ATS [6]. This is sometimes already the case today, which can be illustrated by the following not very unlikely example: Twenty minutes late from Stockholm, you now sit in the airplane on your way to a business meeting. You are kind of pressed for time so you heave a sigh of relief when the pilot catches up the initial delay and touches down on time. Unfortunately though, the gate your plane is allocated to is occupied so you have to wait, strapped for your chair, for about half an hour before there is a free gate and you can enter the terminal.

Even though there might be several reasons for this scenario, it is well-known that delays in general are often initiated at the airport. According to Mueller et al [4], only 16 % of the air traffic delays are airborne, while the rest can be derived from gate (50 %), taxi-out (26 %) and taxi-in (8 %). The example above also shows the lack of communication between different actors, that one delay causes new delays, and that a higher en-route speed may not lead to better punctuality, but instead higher fuel costs and more pollution.

This paper focuses on resource management in the airport system. Resource management in this perspective covers all logistic activities and sub processes – and corresponding resources – that are involved in and influence the air transportation process. We call this Airport Logistics. The vision with airport logistics is to develop a complete picture of all processes and activities at the airport; in particular a real-time overview and controllability over all resources in use, or available for supporting the ATS. With this information at hand, it would be possible to, at a tactical basis, optimize the planning and utilization of all the resources. In this paper, an example of a tactical planning tool, in the form of an optimization model for scheduling de-icing trucks, is presented. The model tested using real data from one of the de-icing companies at Stockholm Arlanda Airport (SA).

In the following section the concept of Airport Logistics is described followed by a presentation of the de-icing process. Subsequently, the planning tool for the de-icing process, which is implemented as a mathematical model solved by a GRASP heuristic, is presented. Finally, computational results from the model are presented and discussed.

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II. Airport Logistics

The existence of the air transportation system (ATS) is due to the demand for quick transportation over long distances, for example between the airports A and B in Figure 1. It is instructive to view the ATS as a network having flows. In this context, the flows that generate value in the ATS are passengers, possibly traveling with baggage, and cargo. These flows will henceforth be called *value flows*. In order to facilitate the value flows, *support flows* are necessary; the two most evident being the flows of aircraft and aircraft crew, here called *main support flows*. These are also the only two support flows that connect the airports in the system.

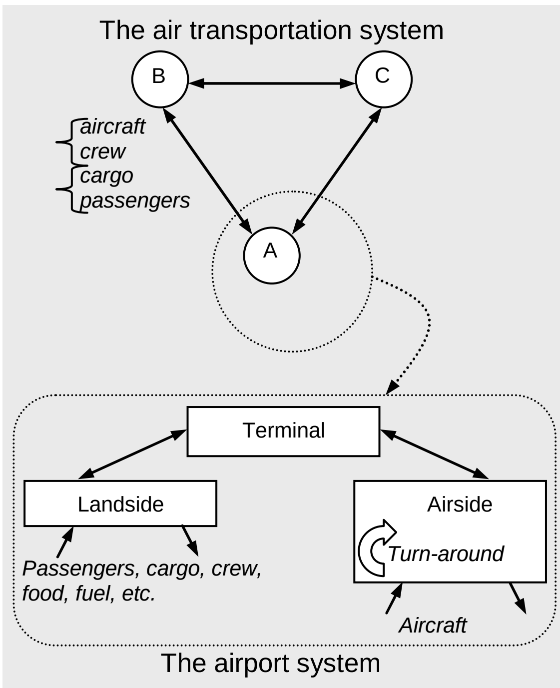

Fig. 1. Conceptual view of the air transportation system and of the airport system

Most users of the ATS interact at the airport. Apart from the airport, which may be regarded as an actor in the system, the users include airlines, handling companies, passengers, cargo owners and air traffic control (ATC). The overall efficiency of the system is a complex function of the individual efficiency of every single participant in the system. To maximize the overall efficiency, the operations of one actor should be made available to all other actors. This is also the core concept of collaborative decision making (CDM). In CDM, airlines, airports, handling companies and ATC should all have access to the same information within the system. An actor should be able to influence decisions that will affect their operations, including decisions made by another actor.

The technical prerequisites for an effective CDM system, such as the possibility to create safe and secure communication channels, exist today. Furthermore, there exist solutions for navigation, surveillance and control of aircraft, which are superior to the radar based systems in use today. These technical advances result in an increasing amount of information to each actor in the ATS, which, correctly used, might lead to improved resource utilization, as well as reduced delays and waste. However, the growing amount of information also leads to a mounting complexity in the decision making process, as the number of options available for the decision makers grows. Thus, improvement in efficiency requires that each actor has the ability to handle and utilize the new information.

When a single airport is studied, the logistics of the ATS is limited to airport logistics. Airport logistics is the planning and control of all resources and information that create a value for the customers utilizing the airport. The customers in this aspect are the passengers and cargo service consumers, as well as airlines, restaurants, shops, and other actors operating at the airport. In the context of CDM, the goal of airport logistics is to utilize and process the information made available via CDM to achieve an efficient resource management. Airport logistics does not only include managing the pure airport processes, but also the relevant ATM and airline processes.

Looking closer at airport A in Figure 1, the airport is divided into three geographical areas; landside, terminal and airside. These are commonly used notations, but the definitions vary. In some sources landside includes all activities on the ground and airside includes everything happening in the air, while other sources place the border between landside and airside at the security control. The definitions used here can be found in Table 1.

The process of unloading passengers and cargo, re-equipping the aircraft and loading new passengers and cargo, is called turn-around. One way of increasing the resource utilization in the ATS is to reduce the turn-around times. During turn-around, several activities are performed; passengers and baggage have to be unloaded, and the aircraft has to be cleaned and fuelled. The toilets have to be emptied and the food supplies restocked.

Table 1
Definitions of Airport Areas

Airside	Airside is the area where activities related to aircraft movements, like approach, taxiing and take-off, as well as turn-around (e.g. fuelling, push-back and services by other types of vehicles), take place.
Landside	Landside includes the areas and the associated activities on the curb side of the terminal, like parking spaces and bus stops.
Terminal	Terminal includes the area and all activities occurring inside a terminal building. Note that this may be a cargo terminal as well as a passenger terminal.

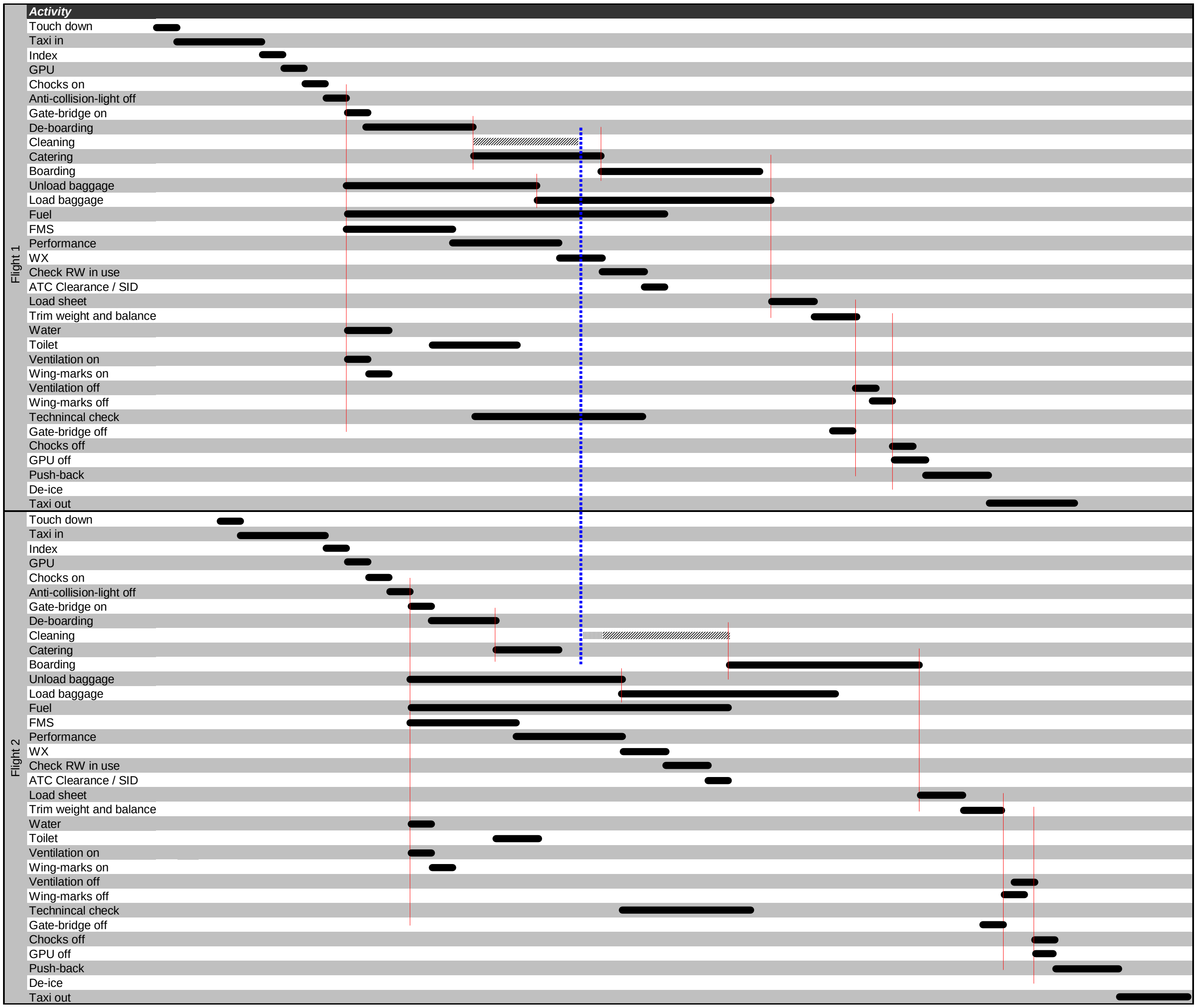

Fig. 2. Gantt charts for the turn-around processes for two flights

Sometimes snow and ice have to be removed before the aircraft can take off again. The efficiency of each of these processes has a direct impact on the turn-around time of the aircraft. The turn-around process is essential in the airport system, as most of the other relevant processes and activities connect to each other during the turn-around. This makes turn-around one of the processes that have most to gain from an efficient integration of ATM and ground processes, as well as an excellent starting point for analyzing airport operations. To plan and execute the turn-around for one single aircraft does not pose that much of a challenge. However, at most major airports, including SA, several turn-around processes occur simultaneously. Many of these processes depend on shared resources, like fuel vehicles, cleaning staff and baggage handlers. If any of these are late to a specific aircraft, the turn-around time for that aircraft might suffer, as the example in Figure 2 shows.

The process times for each activity in the Gantt charts in Figure 2 are based on data from Scandinavian Airlines. Critical activities for Flight 1 include baggage handling, Load sheet and Trim weight and balance. However, it is easy to see that only a slight increase in any of the process times for Deboarding, Cleaning, Catering or Boarding, would create a new critical path and increase the total turn-around time. In the example, Flight 1 and 2 share only one resource; the cleaning crew. Still, the cleaning crew have to finish cleaning Flight 1 and move to the aircraft of Flight 2 (symbolized with vertical lines) before the cleaning of Flight 2 can start. As the cleaning of Flight 2 does not start directly after De-boarding, Cleaning becomes a critical activity. Thus, if the two flights did not share the cleaning resource, or if the cleaning resource benefited from better planning, it would be possible to reduce the turn-around time for Flight 2 significantly.

Notice that the example only includes one shared resource and two flights. In reality, numerous aircraft, with simultaneous turn-around processes, have to share a limited amount of resources, making the planning of these resources a crucial part of an efficient air transportation system.

Every single turn-around can be seen as a network including the value flows and the main support flows. When studying the whole airport, one such network for each turn-around process during the time-span of the study has to be created. The network flows then have to be connected, where transferring passengers, cargo, and crew from one aircraft to another have to be considered. Each of these transfer flows might have a direct impact on the turn-around time for an aircraft. The value flows and main support flows can be connected by combining multiple similar networks. The other support flows, like the flow of cleaning crews or water vehicles, have an impact on the turn-around time as well, but these flows traverse the network in a third dimension, which might be represented with a new network for each support flow under consideration.

A. *The de-icing process*

Since even very thin layers of frost and ice on the aircraft have negative effect on the lifting force and the control of the aircraft, de-icing is needed during the cold period. At SA, the de-icing period is between October and April. The de-icing process is divided into two steps; during the first step, frost and ice is removed from the aircraft, usually by a warm, buoyant glycol mix (Type 1 fluid). The next step is called anti-icing and is performed to prevent new frost and ice from appearing on the aircraft before take off by a thicker fluid (Type 2 fluid). The time from anti-icing to take off (hold-over time) is limited, as the effect of the Type 2 fluid wears off after a while. This means that it is not possible to de-ice an aircraft a long time before take-off in order to find an efficient schedule for the de-icing trucks.

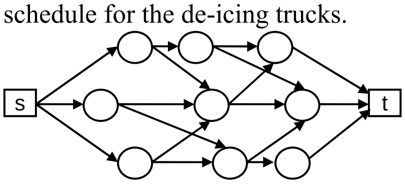

Fig. 3. Network flow problem for a specific support flow

In Figure 3, each node represents a certain aircraft that have to be de-iced within a time window. The squares are the source and the sink for the trucks. Each arc in the network represents a feasible connection between two aircraft; if an arc exists between aircraft A and B, it is possible for a de-icing truck to serve A, travel to B and serve B within their respective time windows. At the beginning of the planning period, there exist a number of de-icing trucks (in the source), that has to serve a number of aircraft. If the aircraft is served late, the turn-around time will increase with a possible late departure as a result. If the de-icing is performed too early, the procedure might have to be repeated. Even so, this would be a fairly uncomplicated planning problem, if only the time-windows were known in advance and could be considered reliable. Today, the de-icing coordinator will plan tactically based on weather conditions and the flight schedule, and operationally – when a truck is dispatched – based on a request from the pilot [2]. In the moment the coordinator gets the request, he or she decides which truck that should be allocated to the aircraft in question. Today, there is no preplanned schedule that the decision can be based on. This means that the truck-drivers do not know in advance which aircraft they are going to de-ice during the day.

The request from the pilot usually arrives in the beginning of the turn-around process, with the assumption that all activities will be performed on time. The de-icing truck will arrive to the aircraft a couple of minutes before the scheduled departure time, and the de-icing process normally takes between three and twenty minutes. If Cleaning is delayed, like for Flight 2 in Figure 2, the de-icing process may not start when it was intended to. This may well affect the turn-around process of the next aircraft that the truck is planned to serve. It might also affect the next aircraft assigned to the same gate.

There are three de-icing companies at SA; SAS Ground Service (SGS), NorthPort and Nordic Aero. This study is based on real data from Nordic Aero during the de-icing season 2006-2007. Nordic Aero has six de-icing trucks with different capacity for Type 1 and Type 2 fluid. There is one location at SA where the trucks can go to refill the fluids when needed, here called the refill station.

III. The Model

The de-icing process can be modelled as a route optimization problem where one objective is to find the shortest total route between the aircraft for all de-icing trucks. Another objective is to find a route that will cause as little delay as possible to the aircraft. This model can be used for minimizing the distance, minimizing the delays or a combination of both objectives. The purpose of the model is to make a plan for the de-icing company, stating which truck that will serve each aircraft and also informing when the trucks should to go to the refill station.

The data received from Nordic Aero is a time-table for the flights. Every row in the time-table is a job for one of the de-icing trucks, here called an assignment. The time-table includes e.g. the scheduled time of departure (STD) for the aircraft, the location of the assignment (i.e. the aircraft stand), the time the assignment was ordered, quantity of fluid used for the assignment (both Type 1 and 2) and identity of the truck used for the assignment. The last variable is the one changed in the model.

A. *Parameters and definitions*

TABLE 2
PARAMETERS AND DEFINITIONS

I_n	De-icing duration time for assignment *n* (minutes)
T_{ni}	Travelling time, i.e. the time it takes for truck *i* to drive to assignment *n* (minutes)
S	Set-up time, i.e. the time span from when a truck arrives to the assignment until the de-icing can start (minutes)
A_{ni}	Assignment time, i.e. the total time it takes for truck *i* to perform assignment *n* (minutes) $A_{ni} = T_{ni} + S + I_n$
E	Expected assignment time, i.e. an estimated time used before the assignment has been performed
R_{ni}	Refill time, i.e. the time it takes for truck *i* to fill up fluid at the refill station after assignment *n* has been finished (minutes)
F_{ni}	Finished time, i.e. the time truck *i* is finished with assignment *n* (minutes). This is also the time that truck *i* can begin the next assignment.
STD_n	The scheduled time of departure for the aircraft corresponding to assignment *n* (minutes)
D_i	The accumulated distance travelled by truck *i* (meters)
D	The accumulated distance travelled by all trucks; $D = \sum_i D_i$
L_{ni}	The delay that truck *i* is causing the aircraft at assignment *n* (minutes) $L_{ni} = F_{ni} - STD_n$ if $F_{ni} > STD_n$
L	The accumulated delay for all trucks, i.e. $L = \sum_n \sum_i L_{ni}$

When CDM is implemented at SA, the de-icing companies will have information about where and when de-icing is needed. Then the request for de-icing from the pilot will not be needed anymore, which makes the use of the order time obsolete in the model. By not using the order time delays caused by too late order time will be avoided, and the finished time is calculated as:

$$F_{ni} = \begin{cases} F_{n-1i} + A_{ni} & if \quad F_{ni} \geq STD_n \\ STD_n & if \quad F_{ni} < STD_n \end{cases}$$

If $F_{ni} > STD_n$ a delay occurs. If F_{ni} is lower than STD_n, STD_n is used as the new finished time for truck *i*. In reality the de-icing trucks sometimes might be available for the next assignment before STD_n but since de-icing in general is the one of the last things that is performed before take off, this extra time will be very short and is therefore neglected here.

B. Assumptions and simplifications

- The model does not regard personnel scheduling, like lunch breaks or shift exchanges. Thus, all the trucks can be used during the whole day and do not have to go to the depot at specified times.
- In the model, all the trucks start at the Nordic Aero depot.
- The distance between the depot, the refill station and the aircraft stands are not exactly measured but estimated from a map.
- The time from the arrival of a truck to the aircraft stand until the de-icing can start (*S*) is based on estimations from the time-table and the same for all assignments and all trucks.
- The expected assignment time (*E*) is estimated is based on estimations from the time-table and the same for all assignments and all trucks.
- When the level of Type 1 or 2 fluids is below a certain level (based on the average consumption of the fluids at one de-icing) the truck has to go to the refill station before performing the next assignment.

C. Real Case

In order to be able to compare the results from the model with the way the trucks are controlled today, the distance and the delays are calculated when allotting the assignments according to the time-table. All presumptions, like when to go to the refill station, that there is no need to go to the depot and how to calculate the delays, are the same in all results, which are presented in Table 2. Note that the delay time is the delays compared to the STD, i.e. Nordic Aero is not responsible for that amount of delays. If any other process, or the preceding flight for the aircraft, is late, the de-icing process will start late, and there will be a corresponding delay.

A few different heuristics of varying complexity, capable of solving the de-icing truck scheduling problem have been developed and are presented below.

D. Greedy with availability check (GWAC)

A greedy heuristics is a constructive algorithm which always chose the element that gives the smallest cost increase [3], which in this case is the shortest distance. The assignments from the time-table are allotted to the truck that is closest to the location for the assignment, if this truck is available (i.e. if $F_{ni} < (STD_n - E)$). If not, the second closest truck is selected (if it is available, etc). If no truck is available, the one with the lowest Fni is selected. When a truck has to go to the refill station, the distance from the current assignment to the refill station is added to the accumulated distance; Dni and the current location and Fni for the truck is updated.

E. Greedy without availability check (GWOAC)

To calculate one of the shortest possible travelling distances, the greedy algorithm is used. In this case the algorithm always allots the assignment to the closest truck, not regarding if the truck is available or not. This does not guarantee the shortest possible distance, but it is an easy way to find a solution with a short distance. Time- and distance-additions caused by going to the refill station is taken into consideration in this case as well.

F. *Multicriteria decision making*

Small delays are not coherent with a short travelling distance, i.e. there is a trade-off between minimizing the distance and minimizing the delays. Such multiple objectives can be handled either by prioritizing one of the criteria and use the solution optimal for that objective, or by trying to evaluate the quality of the results by a function that is aggregating the different objectives [3].

In this case, an aggregate function is created to be able to evaluate both distance and delay in the solutions. The function is called z and is evaluating one minute delay almost as expensive as 1 km of extra traveling distance compared to the shortest distance found, which is the distance produced by the GWOAC.

$$z = ((D - D_{GWOAC})/1000) + L$$

G. *GRASP*

GRASP (Greedy Randomized Adaptive Search Procedure) is an iterative heuristic consisting of two phases. In the first phase a feasible solution is constructed by making a random selection of elements from a restricted candidate list (RCL). The RCL consists of a number of the greediest elements restricted by either value (quality) or quantity (cardinality). The second phase involves a local search around the solution obtained in the first phase. The two phases are iterated until certain termination criterion is reached [5].

In this model, the RCL is based on both cardinality and quality; it consists of the three trucks which are located closest to the assignment, if there are three trucks available. Otherwise the RCL is limited to the available trucks. If all trucks are busy, the three trucks that first will become available are added to the list. The truck selected for the assignment is then randomly picked from the list. This gives a new start solution for every GRASP iteration.

In the second phase, a local search utilizing the 2-opt procedure is used. Local search means that a neighborhood around an existing solution is defined and the solutions found in the neighborhood are evaluated. If one of the neighbor solutions is better than the current, this solution is selected and its neighborhood is evaluated. This continues until a solution has been found that has no better solution in its neighborhood, i.e. a local optimum has been found. One of the easiest local search algorithms is 2-opt, which means that two not adjacent elements swap places with each other [3]. In this case that means starting from the solution from phase one, two assignments that are allotted to two different trucks are swapped between the trucks, i.e. the neighborhood is limited to two trucks. In practice this means that if truck *A* serves assignment 1-2-3 and truck *B* assignment 4-5-6 in the first solution and assignment 2 and 4 are swapped, the new assignments to serve for truck *A* are 1-4-3 and for truck *B* 2-5-6. A swap is performed only if the z-value decreases. A swap can not be performed if one (or both) of the assignments is to go to the refill station. This means that the level of fluid is not recalculated, and the number of assignments for a truck between trips to the refill station is never changed.

The GRASP algorithm is repeated 1250 times and the best solution from every iteration is showed in Figure 4. The lowest z-value found is 794. The same z-value can be reached with different sets of D and L, but in this case only one solution where z=794 is found. The line for all sets giving z=794 is also showed in the graph.

Note that all points in Figure 4 are different solutions from the same input time-table. Looking at the points, it is clear that one solution is dominating in distance and another one in delay. The best schedule to use should be one of these dominating solutions, but which one depends on the objectives of the user. If a short total traveling distance is desirable, the solution to the left is preferable, while the lowermost solution is preferred by those who want to minimize the delays.

IV. Results

As can be seen in Table 2, the delays and the z-values from the algorithms decrease remarkably compared to the Real Case. The delays go from over 7000 minutes in the Real Case to below 800 with GRASP, which is a decrease of almost 90%. The same holds for the z-value. The travel distance in the Real Case is quite good, but it can be reduced with 16% compared to GWOAC. Since the z-value penalizes delay more than distance, the lowest z-value found corresponds to a D longer than that in the Real Case. Although the distance becomes longer, the increase is not large; less than 4% compared to the Real Case. In the GRASP solution dominating in distance, D is about 4% shorter than D in the Real Case and about 13% longer than D in GWOAC. The corresponding delay is reduced to 904 minutes, which is a reduction with 88% compared to the Real Case.

It is interesting that the GWAC algorithm gives a longer traveling distance than the Real Case. One explanation is that the model does not regard the fact that the trucks have different fluid capacity. In the Real Case the trucks have a very uneven usage, where one truck is allotted for 40 assignments and another one only to 4 assignments out of 130. One reason for this unevenness might be that the Real Case uses trucks with a large fluid capacity more frequently. Another reason may be that the unevenness is due to the personnel schedule, i.e. there are not truck drivers for all trucks available during the whole day.

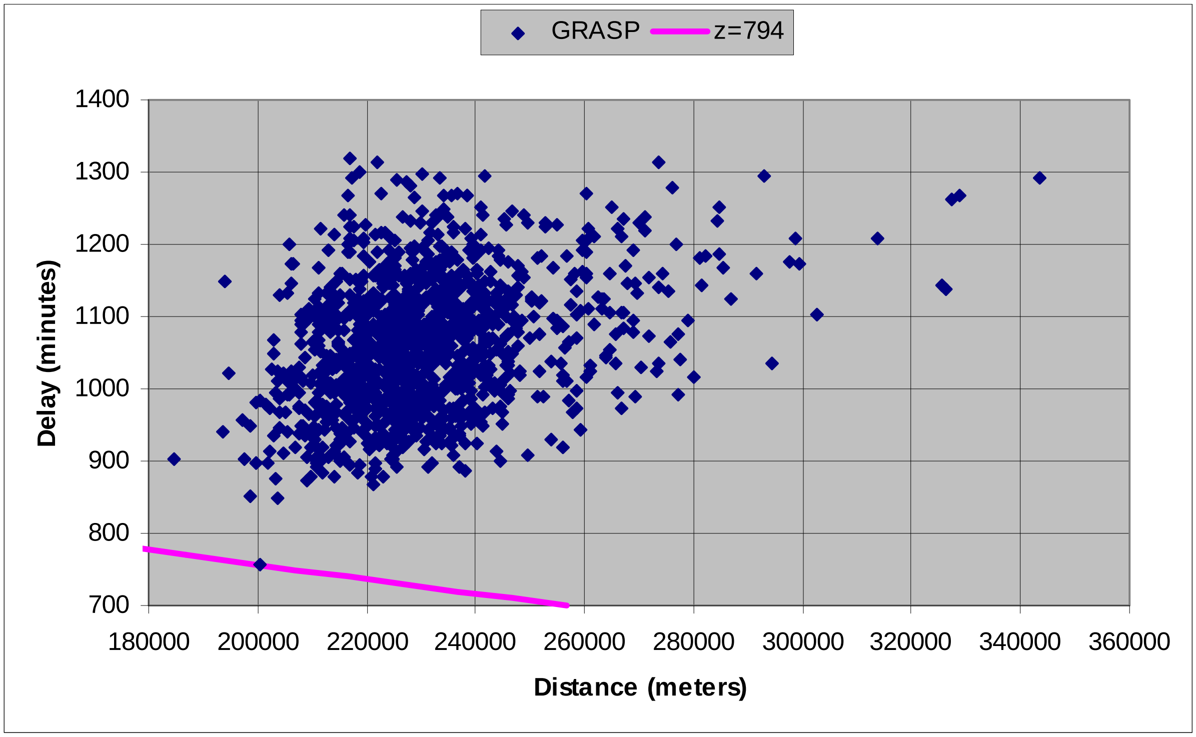

Fig. 4. Solution range from the GRASP algorithm

The results presented here are based on data for one single day, and are therefore preliminary. Running the GRASP algorithm for several iterations may also give better solutions, so the results presented here have no guarantee of being optimal. In any case, the results show a significant improvement compared to the Real Case.

TABLE 2:
COMPUTATIONAL RESULTS

	D	*L*	*z*
Real Case	193 150	7 395	7 425
GWOAC	162 750	12 457	12 457
GWAC	207 600	938	983
GRASP (dominating in *L*)	200 600	757	795
GRASP (dominating in *D*)	184 600	904	925

V. CONCLUSIONS

In this paper we have discussed problems that may arise as a consequence of all actors and activities during the turn-around process being dependent on each other. An example is the cleaning crew being late to one flight and thereby causing delays for both the next flight they are scheduled to clean, as well as the next aircraft waiting to use the gate. If this delay is known by both ground and ATM actors, it may be possible for the next aircraft scheduled to use the gate to slow down and save some fuel. For this kind of planning situation, it would be helpful to have decision support tools integrating both ground and ATM processes that can provide a robust tactical planning, operational dispatching support as well as disruption management support, when the planning fails.

One part of such a tool could be a planning tool for the support flows in the airport system. By optimizing of all the resources for the support flows, i.e. making a plan for exactly which resource (e.g. a de-icing truck) that should serve a specific aircraft depending on the scheduled time-table as well as on upcoming delays, the support resources could be used more effectively. An example of such a decision tool for the de-icing process is described in this paper. Here, the algorithm has been run for a time-table with real data on duration times and fluid needed, in order to illustrate how it could be used on a tactical or strategic level. However, this kind of algorithm could also be used in an operational situation by re-optimizing when new data from a CDM system (or some other airport system) becomes available. In such cases, estimated values of de-icing time, quantity of required fluid etc. have to be used.

The advantage of using this type of algorithms is not only to shorten the distance traveled and decrease the delays, but also to make the actors more prepared for the upcoming situation. Today, the de-icing truck drivers do not know which assignment that will be their next until a very short time before the assignment starts. With this kind of planning tool, the drivers will be able too see, when they start their shift, which assignments that are planned for their truck. Although the plans will probably be changed, the knowledge of which the next assignment is will probably increase the sense of responsibility for performing the assignment in an effective way.

In the Airport Logistic project this kind of algorithms will be developed for all support flows (fuelling, cleaning etc) and used as input in a simulation model. The simulation model will consider the entire airport as well as nearby processes in the ATS, and will be able to show the larger system perspective.

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Enhanced Information Flow and Guidance in Airport Terminals using best Passenger's Visual Perception

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***Abstract*—The implementation of innovative operational concepts for airport terminals as autonomous, adaptive personal assistance to reach significantly higher compliance with the operator's performance targets (maximum throughput, service level and security) is a topic of great relevance. For this purpose a reliable model to simulate human perception and behavior is needed, since man-in-the-loop trials will not be accepted due to security and facilitation constraints. This work presents a concept for modeling human behavior with emphasis on the individual visual perception. Preliminary validation results proof the potential for achieving an enhanced information flow inside terminals to satisfy an ever-growing utilization expected for the future. The airport environment is modeled as a "soft" network, allowing passengers to divert from the formal links, as it is observed in reality. The perception of people acting on the basis of this network is modeled with respect to information location and quality as well as human information processing. Furthermore, we developed a people tracking software to validate the presented research approach. One of the envisaged applications of our model is the test of dynamic guidance system installations, ranging from conventional flat screens over 3D Holographic Displays up to personalized information services on the passenger's cell phone.**

***Index Terms*—active guidance, airport, human perception**

I. Introduction

TODAY, airports have to fulfill several tasks. From the passenger point of view, the building is primarily designed for dispatch (arrival / departure) procedures. These procedures possess different environmental demands which result from security/safety and legal requirements. On the other hand, the airport revenues are increasingly dependent from the non-aviation sector, so the sales through retail. To ensure an optimal combination of the often conflictive requirements the airport operator has to balance also the demands of passengers, and those of the airlines, sometimes even co-owner of the infrastructure.

The presented paper starts with a short overview of so far performed related work at the chair of Air Transport Technology and Logistics (IFL) followed by a status quo description and general trends and future challenges in the Terminal Design Process with focus on the airside. A simulation approach is further presented to allow the modeling of human behavior on physical and psychological levels. The focus is put here onto the visual channel since our environmental perception depends on it at a level of 80-90% [1]. The human behavior modeling forms one new element of a simulation tool for passenger motion which was developed at IFL for emergency simulation purposes. It further comprises a converting process allowing to transform physical buildings into a mathematical network, the generation of passenger traffic on that network based on flight plan data through a microscopic approach and a report and visualization module.

The institute of Aviation Technology and Logistics performed research on several projects which are directly related to terminal processes. These projects dealt with both safety and security aspects. During the project "S3 – security from seat to seat" the initial concept for this simulation environment was developed, able to simulate human motion behavior under several circumstances. Starting with a special focus on airport concepts for hazardous situations [2] and modeling of emergency operational sequences [3] a simulation model for the unpredictable dynamic behavior in emergency situations [4] was developed. In this context a first graphical interface was presented [5] to visually support the analysis of emergency procedures. Consequently the simulation model were used for related tasks, such as analysis of boarding procedures to ensure minimal boarding/deboarding time under consideration of robust, reliable passenger behavior assumptions [6] or studies for adaptive guidance systems at airport terminals[7].

After evaluating different procedures of boarding from aircraft view, suitable and specific terminal configurations for current (A380) and future aircrafts (AC 20.30) could be found [8]. With the present research results the model seems well suited to investigate for innovative airport concepts focusing on the efficient use of all facilities at varying operational constraints.

II. Trends and Challenges

A. Status quo

Airport terminals exhibit grown/emergent structures. For

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decades airport expansions were based on past design decisions and so often face long-standing restrictions. Due to the steadily increasing amount of passengers (up to 20% at selected Airports in Germany, ADV 2007) airport operators are faced with the urgent need to optimize all dispatch processes. But optimization is not only targeted towards higher passenger flows. In the past years legal changes and growing security constraints are consuming significantly system capacity. For instance, passengers are faced with enhanced legal restrictions for baggage control (hand baggage) and airports have to handle additionally these baggage issues requiring more space (see North America Airport Satisfaction Study from J.D. Power and associates, 2007). With the efficient use of limited sources (e.g. capacity) a high system load can be reached while increasing the error tolerance of the whole system. All parts of the whole system have to work as planned to ensure system efficiency.

Passenger perception and needs are not substantially considered in airport processes. One representative example is the level of service (LOS) concept. Based on Fruin's work [9] standard indicators for terminal dimensioning (e.g. average speed or density) were developed and adapted (see [10]). These indicators reflect only airport opinion about passengers needs. From the passenger point of view there might be different key indicators. The guidance system as an essential part of the superior airport concept can be taken as an appropriate example. The passenger explores the airport by using the guidance system, so naturally airports have to be very sensitive to the needs of passengers for clear information. In this context Mijksenaar [11] refers to the Global Airport Monitor survey of the International Air Transport Association [12] that the second highest rated airport service item is the "Ease of finding your way through the airport/signposting". Airport standards regarding to the corporate identity often have a higher priority than passenger perceptions or efficient way-finding concepts. Additionally, airport operators have to balance both passenger needs for way-finding and the airport demands for revenue-earning (advertising) signage. Passengers, who are not familiar with the complex airport environment, are strictly relying on way-finding information. The lack of information has an explicit influence on passenger service perception. The connection between passenger service perception and information providing was already pointed out by Martel and Seneviratne [13]; so essential criteria for walkways (movement areas) are information (53%), distance (38%), available space (6%) and altering terminal level (3%).

Although this fact has already been known for at least 15 years neither legal requirements nor explicit recommendations ensure passenger satisfaction concerning guidance systems. Passenger perception is still disregarded in common service indicator definitions. Thus, without fundamental changes future concepts will be hard to implement in current environments. As mentioned above one problem of existing systems is the inadequate information provision to passengers. At first airports should consider adequate passenger signage. The second step is to provide the right information at the right place and time. Static signs provide information in the right context (environment) that means if a passenger is not allowed to enter a special area a prohibitory sign will advise accordingly. Information placed in the wrong context offers no clear mental connection to a given situation. Due to "news overload" the passenger generally will filter these to get his information judged as having priority. Providing directly addressed information may be one important challenge for future airports. The central question arising is whether existing systems are able to fulfill future communication needs as well.

B. Future Challenges

To develop dynamic guidance systems for terminals three restrictions of the current system have to be resolved. At first static information signs are not flexible enough to handle short term requirements. Display solutions require higher infrastructure efforts (expenses), but the content of the display can be changed immediately depending on current situations. To address information directly to each passenger its location with regard to the passenger's intention (context) has to be identified. For this position estimation visual surveillance systems or active identification (e.g. cell phone signal) could be used. To get a reliable predictor for passenger motion intentions a process classification is essential, for instance which process stage is reached (e.g. check-in). Coupled with a personal profile and his available time budget inside that process state, suitable information may be provided. Besides the passive estimation of passenger's needs a direct communication via personal displays ("Don't hesitate to ask!") will be more efficient and does not rely on accumulated data repositories.

Provided information on public displays could only have general character. These displays are efficient at special terminal areas where nearly all passengers have the same intention; for instance at check-in where additional flight information or remaining time could be provided. To access passengers individually, a personal information display would be needed. Given today's technological level for personalized communication systems, a passenger carries several electronic systems. Typical systems are cell phones (propagation of 96% in Western Europe, see figure 1), personal organizers, MP3 players, portable play stations or laptops.

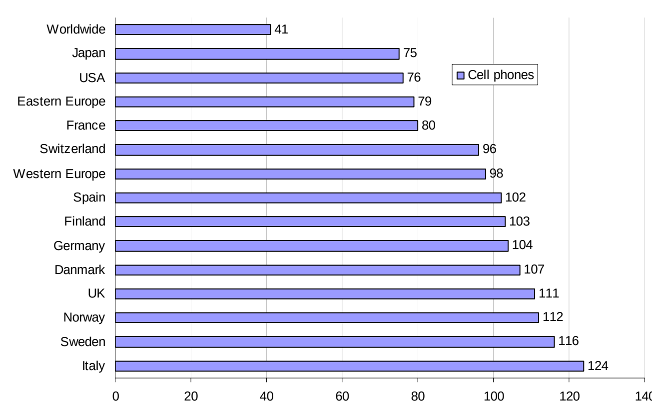

Fig. 1. Cell Phone Propagation, [14]

On a closer inspection and regarding the development of electronic devices the combination of all functions of the mentioned systems to one personal display seems obvious (e.g. Apples iPhone). For example, cell phones already have built-in navigation systems and MP3 functionality.

In the context of general and personal displays, two information propagation approaches have to be differentiated; the push and the pull concept. Classic push mediums are television or radio whereas a classic pull medium is the internet. At television, information will be passively propagated based on assumed customers needs, only. The information gathering at pull media performs differently. The user offers his intention by searching for special key words and a filter engine presents relevant information. Contrary to the television the relevant information bandwidth and the level of detail is much higher. Today the internet is used by at least 53% of the Western Europe inhabitants (figure 2) and 44% of the EU population has adequate computer skills [14].

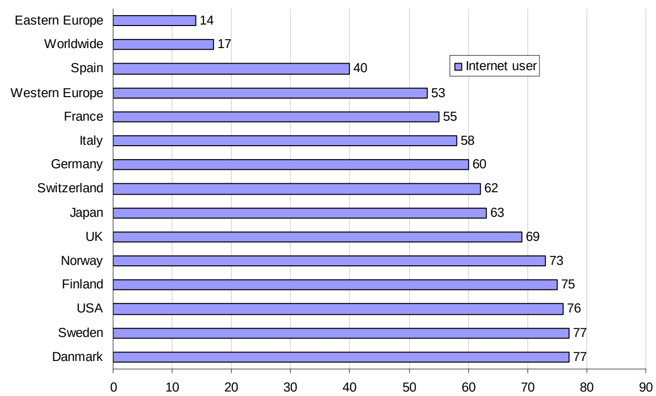

Fig. 2. Internet Usage, [14]

Regarding the high propagation of cell phones and the increasing internet usage the acceptance of personal electronic devices for getting individual assistance or context information will be increase as well. To achieve an efficient communication level between passengers and the airport information system, personalized and context based information have to be provided. Intelligent and powerful information systems will need contactless human-machine-interfaces (HMI) which are primarily focused on ease-of-use.

In a small movie produced by Chris Oakley in 2004 ("The catalogue") a future environment was presented in which each person is identified by video surveillance techniques and matched with personal profiles (see figure 3). At the first impression this scenario has a scary component: the presented surveillance system works as a global data collector and merges all received information to personal profiles. The individuals will consequently loose control of their personal data processing. On the other side knowing the needs of all persons can improve communication quality. Furthermore with the increasing amount of collected data, public and private institutions wish to have a direct access to this data. In the past surveillance systems did use collected data beyond the intended purposes, often with apparent security arguments. Thus, the initial idea to establish efficient information systems ends in a totally surveyed and controlled environment. The introduction of new technologies has to be consequently accompanied by a critical assessment of all positive and negative effects.

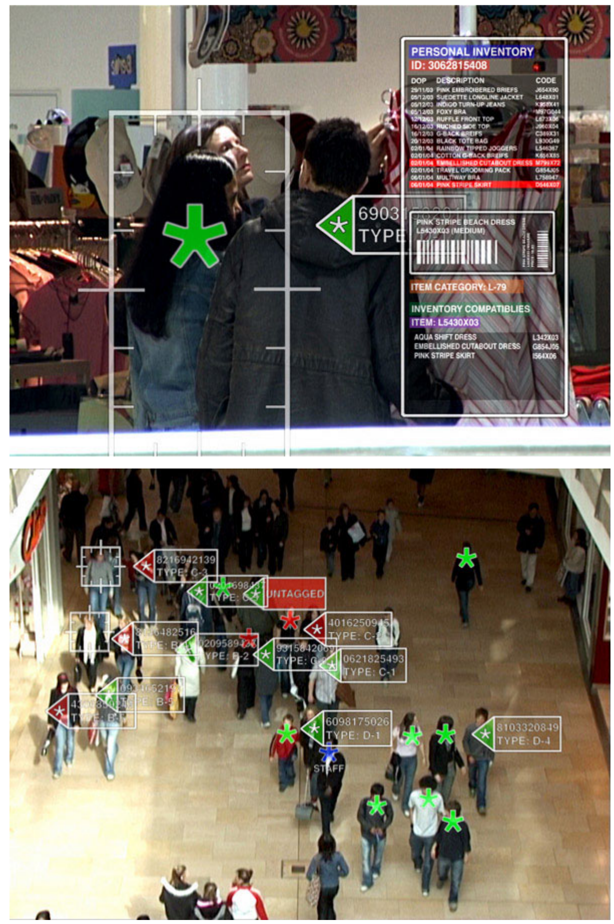

Fig. 3. High level passenger surveillance (see Oakley, 2004)

To accomplish the future trends and challenges in the public transport and information sector, it is necessary to analyze possible consequences and system requirements beforehand. For this purpose the construction of a virtual reality environment presenting the airport terminal is an appropriate method. Thus, the following paragraphs introduce a reliable simulation approach for human motion behavior in complex situations.

III. Simulation Approach

The used mathematical model for human behavior based on a stochastic approach to handle the unpredictable behavior and individual path deviations [4], [16]. Interpersonal interactions which lead to attraction and repulsion effects will be considered by a social force approach [17]. The human motion model is subdivided in an operational and a strategic/tactical part. At operational level the direct interaction with the environment (position change – "make a step") is defined via a stochastically mathematical transition model. The chosen simulation approach [18] additionally handles the human motion with a tactical behavior component. That means both gathered information and the perception of the surrounded environment have influences on passenger's decisions.

Basically each virtual passenger has to implement three functional elements: a sensing system, a planning system and a transaction system [19]. These elements are implemented in human behavior model via a Sense-Plan-Act (SPA) approach [20]. The sensing component provides surrounding conditions for an inner environment model. The individual decision based on the interpretation of the environment model data, previous experiences and actual passenger objectives. In consideration of available alternatives a motion action will finally realized (see [21]). Simulated subjects that implement all the above listed features are called agents. An agent has the capability of flexible and autonomous action, by means of responding to environmental changes, proactive/goal-directed activities and social behavior pattern [22]. A major characteristic for this type of simulation approach is that an agent has almost incomplete information and limited perception areas. Autonomous agents do not need a global system control and computation of position updating is asynchronous implemented.

A. Visual Perception of Passengers

Due to fact that 80-90% of the information will be admitted by the visual channel [1] the model sensor approach focused on the visual system. As shown in figure 4 the visual perception of humans can be defined via a zone approach. Individual limitations for object recognition are at vertical range of ±15° and ±62° at horizontal range.

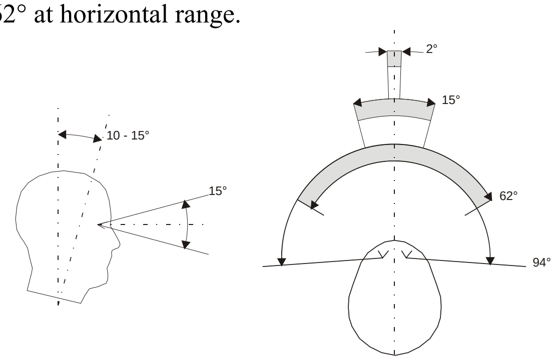

Fig. 4. Human perception area

Additional attention should be paid to the fact that the head is normally inclined to the floor by 10-15°. The horizontal visual range is subdivided in several areas. One eye has a visual range of approx. 160° whereas the intersection area of both eyes has a range of approx. 120°. Objects which are inside this sector are recognized in three dimensions. Furthermore, humans are able to clearly identify objects (as text) if they are located near the focal point (±2°). The range between ±15° is an area with particular attention adjacent to an area of peripheral visual perception (±94°) (see DIN 33414 E / Part 1 and DIN 33402). Information gathered by the agents is additionally tagged with the corresponding perception area.

Information presented on signs is recognizable up to a certain point. Important factors for sign recognition are contrast, brightness, letter size, and information level. As shown in figure 5, the probability of recognition decreases with the distance (the presented curves have only general character).

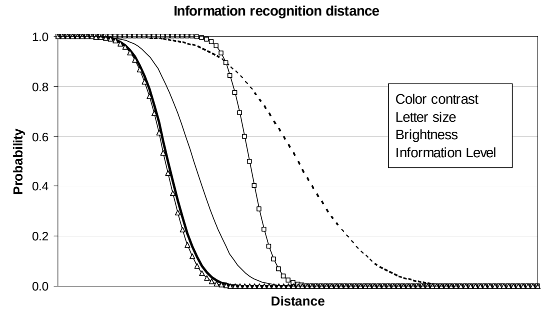

Fig. 5. Sign recognition distance

By using a normal distribution approach (3) for each factor, the mean value μ represents the threshold distance at which an average passenger could / could not get the provided information and σ is the corresponding standard deviation. Probability p of sign recognition is given by

$$p(d,a) = \prod_{m=o}^{M}\left[\left(1-\int_{0}^{d} f_m(x)\,dx\right)\; g_m(a)\right] \tag{1}$$

with the constrains

$$\mathrm{d} = \|\vec{\mathrm{r}} - \vec{\mathrm{s}}\|\,,\; a = (\vec{r}-\vec{s})\vec{n}_s\, d^{-1} \tag{2}$$

$$f_m(x) = \frac{1}{\sigma_m\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{x-\mu_m}{\sigma_m}\right)^2\right] \tag{3}$$

$$g_m(a) = \begin{cases} \lambda_m + (1-\lambda_m)a & \text{for } a > 0, \quad \text{with } 0 \le \lambda_m \le 1 \\ 0 & \text{for } a \le 0. \end{cases} \tag{4}$$

The probability p depends on distance d and the cosine a. The distance is calculated by using the sign position ***s*** and the person position ***r***. The normal vector of the sign $\boldsymbol{n}_S$ is required to determine a. The function g_m is a weighting factor to consider the angle dependence, with non-zero values if the person stands in front of the sign. The degree of angle dependence can be calibrated by changing the calibration parameter λ_m. The combination of all partial factor probability distributions (assuming that all factors are statistical independent from each other) results in the overall sign recognition probability distribution depending on distance d (visualized at figure 5). In the following approach the factors for information recognition will be reduced to the letter size. Based on the previous assumption of an average passenger with no visibility restrictions and normal lightning conditions the functional dependence between letter size h [m] and recognition distance can be determine with μ = 300 h (see DIN 1450) and a standard deviation of $\sigma = 0.05\,\mu$.

To model the overall information gathering process the individual viewing direction, the visual human perception areas (figure 4), and the sign recognition distance have to be taken into consideration. As mentioned above due to human visual limitations the sign has to be at least in the particular attention area to grab the provided information. An example for the distance dependency is given at the following figure (figure 6, compiled by the visual interface). Corresponding to figure 4 the human perception area is subdivided in zones: the inner area of particular attention (sharp), the area which are observed by both eyes (middle, slightly blurred) and the outer area of peripheral perception (out of focus). At figure 6 (top) a person could notice the sign but can not get the information. If the person is getting closer into the recognition area of the sign (figure 6, bottom) and person is looking direct at the sign the guidance information will be received (according to figure 5).

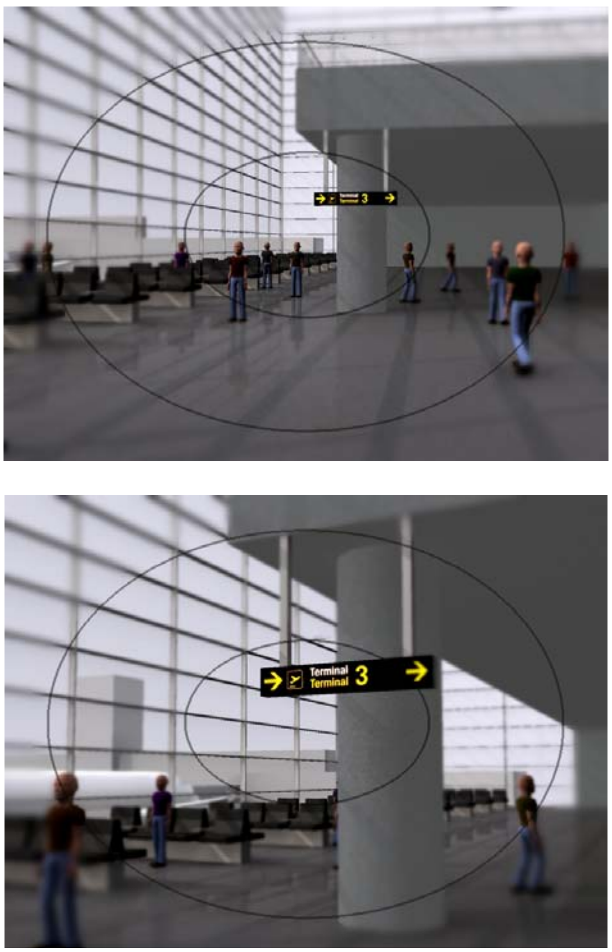

Fig. 6. Perception from passenger's view (far and near)

In addition to the reliable simulation component the visual interface allows to display the simulation results immediately. Existing visual display concepts do not allow to configuring the whole graphics pipeline but this is necessary to adapt the environmental needs (user and programmers) of a custom scenario. At least an appropriate method for the exchange of 3D data between simulation and visual component has to be defined.

B. *Graphical Interface*

The realistic 3D representation of virtual humans [23] is one major part of our concept. The convincing demonstration allows a first plausibility check and leads often to optimized design solutions (see figure 7). Not only the end user benefits from visualization, also developers need immediate visual feedback. The used visual interface is a flexible tool for graphical representations of animated virtual humans. The Visualization can be separated from the simulation process; existing approaches tend to couple those two aspects very strongly. A graphical system should not only work with a specific simulation model. The tool supports the animation of a crowd scene, particularly the automatic generation of human locomotion from trajectories.

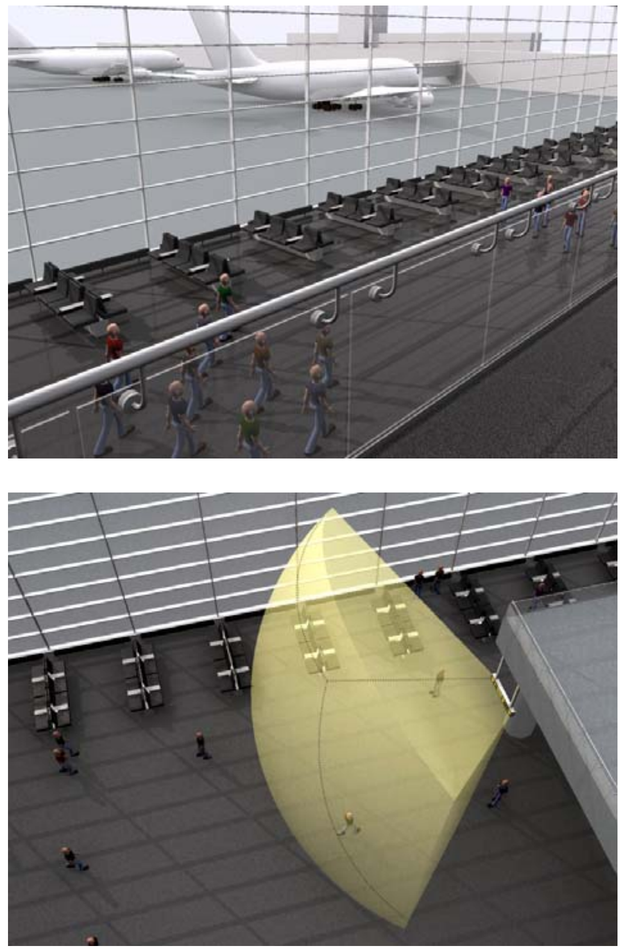

Fig. 7. Environmental overview and sign perception area, compiled by visual interface

Rendering several hundreds or even thousands of characters in real time presents a challenge which has not been fully addressed up to now [24]. Using the latest features of the Graphics Processor Unit (GPU) is essential to cope with these high computing power requirements. The OpenGL (see [25]) standard and a so called shading language give access to the capabilities of a GPU. The tool is built on sophisticated Open Source software, resulting in no licensing issues for both academic and commercial use. High requirements for future scenarios in the 3D environment demand that the whole graphic pipeline have to be adapted by forward-looking technologies. Java and the Eclipse Platform (see [26]) provide reusable standard components for fast software development. The freely configurable 3D environment is an autonomous component with an interface connection to the underlying simulation model. The modular design allows changes at behavior algorithms without influencing the graphical output. A potential bottleneck could be the communication between all processes which needs to exchange the displayed data. There are a lot of commercial applications for the creation, editing and rendering of 3D data. Instead of reinventing existing features, a better approach is to standardize the communication between those applications. The preferred Collada format (see [27]) is the first non proprietary 3D data exchange format which is especially suited for being a communication interface between applications in the area of real time content production.

C. Network Approach to Design the Investigation Area

To simulate the airport environment the terminal building is transferred to a logical model. This model contains every primary and secondary destination. If the logical structure of the building is generated, all possible connections between the referred destinations are set up. A simple logical model is shown in the following figure (figure 8).

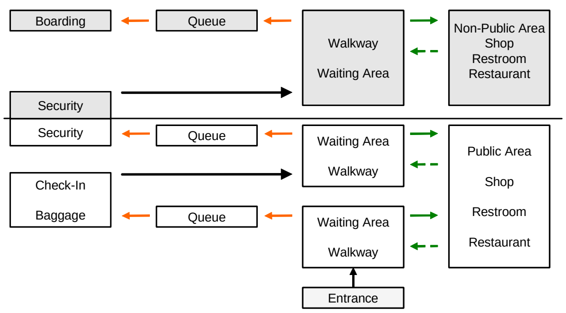

Fig. 8. Logical process chart

Entering a primary process is often coupled with accessing a queue. Before accessing the queue passengers may choose between primary and secondary facilities. The decision depends on the remaining time. The first requirement for passengers is to reach the check-in in time, because many airlines close the check-in counter 30 min before the scheduled time of departure. The arrival time of passengers depends on several factors, like individual expectations and experiences regarding terminal processes as well as the travel motivation (business, leisure) and travel distances. For this reason departing passengers arrive at the terminal in the range of 2.5 hours to 30 min before scheduled [28], [29]. If passengers have finished the required departure procedures they are free to spend their time for different activities until boarding. Frequent and business travelers usually minimize their inevitable airport time whereas other passengers tend to considering extra time.

An appropriate LOS and well-defined guidance instructions consequently induce short process times. If the available time budget exceeds a sufficient level a substantial increase of consumption activities by the passenger takes place [30]. In the logical process chart (figure 8) decision points are located at the walkways. Without considering concessionary facilities all routes connecting the primary arrival and departure facilities are created. In this process the terminal design and geometric characteristics are considered as well as the maximum capacity of the path sections and appropriate service measures.

In the showed network (figure 9) vertices (circles) represent facilities and edges (arrows) are the connection in-between. According to the intention of optimization the edges have different weightings. In a second step edges are split by adding a decision point (grey square) with connection to the retail area (rectangle). As a result a directed graph representation of the terminal can be used for further network analysis and optimization [31].

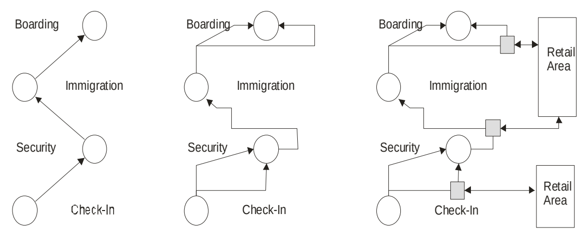

Fig. 9. Network representation of a simplified terminal

If the network approach is merged with the passenger simulation model and the visual interface a powerful software environment can be generated which is able to describe all terminal processes. At the first step the impact of different kind of signs can be evaluated inside the simulation environment. Based on the reacting of the virtual humans optimized scenarios can be developed.

D. Model Validation

To validate model parameter a test set up at Dresden airport is planned for winter 2007. This setup primarily focuses on passenger reaction to provided guidance information. The reaction will be recorded via a prior installed video system. With respect to privacy legal requirements the recognition of motion behavior will be handled by an automatic real time software environment. According to this real time calculation a manual post processing will ensure that only consistent trajectories will be used for the analysis process.

There are several motion capture techniques to track passenger movements. A primarily used approached is the separation of background and foreground data. Generally background data are static that means they are not changing during time. The easiest way is to take a still image as background before the test is started. Due to influences of lightning variations an additional time dependent background adaptation approach (see [32], [33]) is implemented. If changes between the current picture (n) and the picture before (n-1) are taking into consideration as well an identification of moving and not moving objects can be realized.

Once the (adapted) background image is created, the foreground picture can be compiled by subtraction of current frame and the stored background image. The following figures demonstrate the result of this separation process. The separated foreground image at figure 10 only contains moving objects. On figure 11 the background image is shown in conjunction with static objects (normally stored in an own layer).

Figure 10: Separation of foreground (inverted)

Figure 11: Separation of background with static objects

If the video source has a good quality the noise of the foreground image is low. To reduce the noise the picture will be converted to threshold filtered grayscale image. The result (mask) is shown at figure 12. From this figure so called regions-of-interest (ROI) can be created; areas which contain the specified objects (in this case moving persons).

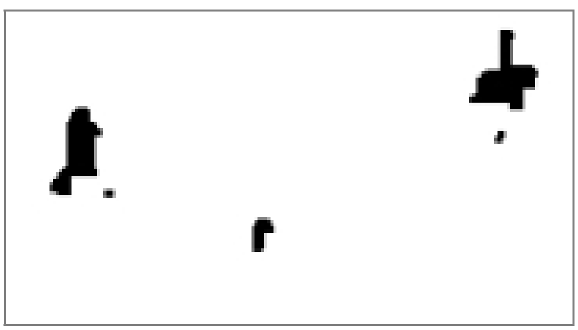

Figure 12: Mask creation (foreground threshold)

The ROI's are marked with squares at figure 13 and they are the basis for the following computer vision algorithms.

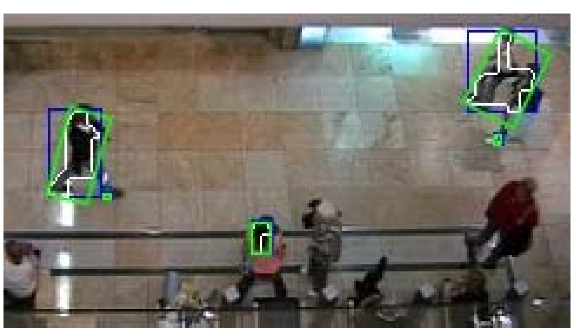

Figure 13: People identification (regions-of-interest)

Due to the fact that a ROI only contains moving particle, the next step is to extract the person itself. The person on the left position could be clearly identified but the two persons in the upper right corner are marked as one object. If the moving object could be clearly identified as a person it will be stored in a database. All identified person of the current frame will be compared with the persons extracted from the past frame. The comparison will be done by several parameters: person distance, contour shape, moving direction, speed and color gradient (histogram). If there is a strong correlation (> 0.9) between the current and a stored person the motion path of the stored person will be extended and the parameter set will be slightly corrected (adaptation). If there is no match the person will be stored in the database as a new entry.

Crowded areas have a high potential of false detections. To reduce the false results more sophisticated algorithms or manual corrections are necessary. Under consideration of the real time component and the essential need of manual interventions the application of high sophisticated algorithms are only preferred if the computer has free calculation capacities.

The developed software tool allows tracking the path a person takes. The simulation environment for virtual humans could be used for estimate the real motion behavior, but these estimations have to be validated with the motion patterns/paths of real persons. For the special purpose of observing motion behavior (especially information gathering) a field trial is essential.

E. Combination of Components

All the presented software components, the simulation environment of passengers with the extended visual perception, the visual environment, the network approach for terminal modeling, and the video based analysis of real motion behavior are ready for application. In cooperation with Dresden Airport the terminal design will be used to establish the airport environment and to simulate and analyze the route choice behavior of passengers. In a second step, the installed guidance system will be optimized under both passenger and airport requirements.

Passenger requirements are primarily based on having an adequate information level whereas airport requirements are rather aiming at efficiently use the capacity of all facilities. Furthermore safety and security aspects have to taken into consideration as well. After optimization of the existing static information (and guidance) system, the application of future information technologies is the actual challenge. As mentioned in the trends and challenges section, efficient propagation of information can only be achieved by a combination of general and individual/personalized information displays. With the developed software environment we are able to evaluate the influence of these displays on current procedures.

IV. Outlook

Innovative transportation and information concepts for sensitive infrastructures such as terminal buildings require sophisticated simulation capabilities prior to physical tests in the operational airport environment. This purpose can be achieved with the model presented here. Time dependent guidance of passenger flows can also be a major contribution for safe and secure airport procedures.

On the application level, the influence of adaptive airport signage to passenger flows offers the opportunity to increase airport revenues. Efficient use of concessionary area and a good service level based on passenger perception may increase the efficiency of the facility so to cope with the demanding SESAR requirements for 2020 regarding capacity, security and business orientation.

To further verify the simulation results the people tracker developed will be constantly improved through robust computer vision algorithms. Since tracking passengers at highly crowded locations (e.g. check-in areas) is a demanding task, a manual post processing shall be avoided prospectively to achieve this processing in real time conditions.

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Innovative Decision-Making for Decision Support Systems

Charles Tijus and Patrick Brézillon

***Abstract*— Aid for Innovative decision-making is one of the techniques Decision Support Systems should provide to the user. Contrary to modeling analogy, we propose an approach based on problem solving through the finding of substitutes with contextual categorizations that could help having insight solution and through the use of contextual graphs to evaluate how much a substitute is of help.**

***Index Terms*—Contextual categorization, Contextual graphs, Decision support systems**

I. Introduction

ARCHIMEDES had a problem. King Hiero of Athens purchased a new crown for the statue of God and asked Archimedes to find out, without perturbing the wreath in any way, if the crown was really made out of pure gold, or if it was contaminated with cheap silver. Archimedes could not come up with a solution. After a long day of worrying, he decided to relax with a warm bath. When he entered the tub, he noticed the water level rising. This was something he knew, but now he suddenly realized the water displacement was proportional to the volume of the immersed part of his body. He puts a weight of gold equal to the crown in a bowl filled with water. Then, the gold is removed and replaced by the crown. A difference of lighter silver would increase the bulk of the crown and cause the bowl to overflow. He found a way to determine the volume of the crown, and thereby discovered the solution to his problem!

Being a true story or being a fake, we get here the description of a problem solving that is based on the analogy between Archimedes body and the crown from the viewpoint of a procedure use and its results. Such an insight would be appreciated from a DSS as long as the problem at hand does not require a simple solution. We discuss here how to improve DSS with some innovative data analysis that should improve problem solving and creativity indecision-making.

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First, the use of DSS is to make a more rational decision, the kind of decision, at a first look, far from what Archimedes did. King Hiero should have surely dismissed Archimedes telling the story "*I got the solution: I took a bath*!" Second, Archimedes' decision is made of few data, when developed theory made use of large amount of data processing (graphs, statistics), of relations processing (dimensional modeling, data mining, etc.), processing generally made on line with regards to data quality. Thus, our proposal is not an alternative to usual DSS approach, but some way to get an additional look on the data, which would be often biased, either for fun (frequently), or for insight (rarely).

Analogy making is one of the human performances that computer scientists have tried to model and simulate. We first present the limits of analogy and the contextual categorization approach. Second, we define what is the problem of finding innovative solution. Then, we present Contextual Graphs (CxG) as a tool that could be useful for testing innovative decision-making.

II. Creativity as Contextual categorization

Wayne Zachary [18] has listed six classes of DSS techniques that are:

- Process models, which assist in projecting the future course of complex processes;
- Choice models, which support integration of decision criteria across aspects and/or alternatives;
- Information control techniques, which help in storage, retrieval, organization, and integration of data and knowledge;
- Analysis and reasoning techniques, which support application of problem-specific expert reasoning procedures;
- Representation aids, which assist in expression and manipulation of a specific representation of a decision problem; and
- Judgment amplification/refinement techniques, which help in quantification and debiasing of heuristic judgments.

Among these classes, we discuss of analysis and reasoning techniques, more precisely "in modeling the ill-structured, early stages of the strategic decision making process" [13] that includes analogical reasoning.

In the realm of DSS researchers and developers, we often use analogies to explain our ideas about DSS (e.g. [14], or for providing explanation [12]). As a DSS technique, could the use of analogy processes provide the kind of heuristics expressed in the Archimedes story?

Case-based or analogy-based systems try to find on large amounts of data analogous cases, or analogous decision-making situations. According to Gentner and Toupin [6], the finding of possible sources for analogy is as follows. First, the goal being defined (the crown and the problem of finding if the crown is only made of pure gold), a matching process starts by carrying out a large number of comparisons between the components (objects, objects attributes and relations) of the sources and of the goal. Second, source and structure are mapped for "global" identifications. Ripoll and Eynard [11] discussed the order of the successive phases (encode target, find sources with local matches, match structure) in human analogical processes and there is the problem of how components are selected for mapping [10]. However, since analogy is based on similarity with already encoded data, there is not really innovation in the results. There is no difference between case-based reasoning, that is intra-domain, and analogical reasoning, that is inter-domains, in purveying insight: since the creative process is new: Archimedes had never used water displacement for computing the volume of a possible source.

In our introductory example, Archimedes did not solve the problem with his body in the past as required by case-base reasoning or by analogy-based systems. Archimedes got the target problem, solved the source problem, and at the same time, was solving the target problem.

Thus, our first proposal is that Archimedes' cognitive processes are based on recognizing and identifying the crown as the same kind of things than his body from the viewpoint of the water-level rising. Thus, this is categorization problem. We follow Tijus, Poitrenaud and Chene [16] and argue that categorization is not guided by similarity, but, conversely, similarity is guided by categorization.

Our second proposal is that creativity, - as a process of discovery -, is generally related to problem solving, even for artistic creativity [15]. Problem solving means a goal to reach (finding a solution). For Archimedes (or someone else without the solution), the goal could have been that "*the crown and the same weight of pure gold should have the same volume. Thus how to find the volume of the chased crown without destroying the crown?*" What we do know from problem solving is, when in impasse, people that are asked to solve a difficult problem, either make a lot of trials with errors, or stop and start thinking about why the goal cannot be reached and what could be a good position for reaching it, and the conditions to be satisfied to be in that position [19]. Consider the chess game. For example, "*If the Queen was here, I would win! Where is my Queen? Is it possible to have a series of moves leading the Queen there?* " And with counterfactuals: "*what a pity, it would be so simple if I still get my Queen!*" Why having these kinds of assumptions, hypotheses and counterfactuals?

Second proposal is that making counterfactuals is the key of innovative problem solving.

Our third proposal is that counterfactuals based insight is related on the selection of candidate objects by contextual categorization. Archimedes (or someone else without the solution) could think that the problem would be simpler "if kings had a gold cube on their head instead of chased crown!" Why "cube of Gold"? "Cube of gold" is a counterfactual that would be inferred while searching how the problem could be solved. This is realized by searching the objects that would be a solution of the problem, and then by computing differences: How much the solution object differs from the actual object? How to reduce their difference? For example, Archimedes could have found that he cannot transform the crown in a cube, but it could mould it. Having the idea of something that envelops the object, while taking a bath, Archimedes could have then noticed that the water was enveloping his body and could have seen the water displacement.

These three assumptions are modeled through contextual categorization: objects belong to contextual and goal-based categories. Consider the problem presented in Figure 1.The problem is to find the measure of the black surface given x, y and z. An insight would be as follows "*the problem would be easier if we had to measure the white surface instead of the black surface!*" Since the solution is found for the white surface as a smaller rectangle, the insight solution for the black surface is obtained as the difference between the large rectangle and the small white rectangle.

We have seen that the solution requires (1) a "substitute" object (the Archimedes body, the small rectangle in Figure 1) and (2) a procedure (or practice) to be applied to the substitute object. According to Gombrich [7], using substitutes is one of the main processes of imaginary.

In the following sections, we present how contextual categorization can be used to model insight solutions: for finding substitutes and contextual graphs to evaluate the solution procedures. Contextual categorization allows creating a category hierarchy that assembles sets of candidates for substitution. Contextual Graphs formalism is a technique for describing solution paths to a goal, through the set of possible procedures or practices. The whole approach is objective, reproducible and verifiable.

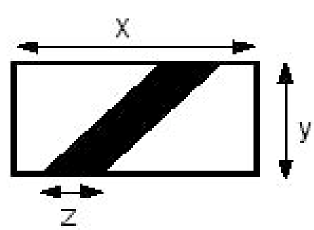

Fig. 1. A simple insight problem: finding the surface of the black part of the rectangle.

III. Contextual Categorization

Contextual categorization is about the building up of a network of categories to catch relationships between objects that are currently processed. For instance, the processing of objects in Figure 1 is to build up a network of categories (Figure 2) of the three basic elements that are the whole black and white rectangle of length x and y, the white surface and the black surface. The black surface has length z as side property and its surface measure is to be found.

a	WhiteSurface	BlackSurface	BlackAndWhiteRectangle
partOfRectangle	1	1	1
black		1	1
white	1		1
lengtht-x			1
length-y			1
length-z		1	

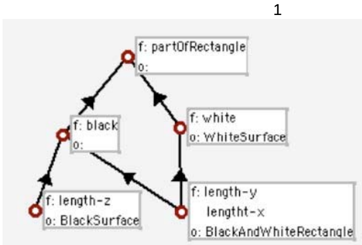

Fig 2. The contextual categorization of objects pictured in Figure 1.

Note that the problem to solve in figure 1 is about the Black surface, which is the black part of the Black and white rectangle. The counterfactual "the problem would easier if we had to measure the white surface" is derived from the opposite category: the non-black surface that is the White part.

Contextual categorization model operates on Galois Lattices in the ProcOpe formalism [16] to create a hierarchy of categories with transitivity, asymmetry and non reflexivity. When given the O_n x P_m Boolean matrix which indicates for each of the n objects, O, if it has, or if it has not, each of the m properties, P. The maximum number of categories is either 2n-1, or m if m < 2n-1, in a lattice whose complexity depends on the way properties are distributed over objects.

Contextual categorization operates also from sentences with the building up of all of the implicit and explicit categories. For example if someone tells that "Peter bought a car", conveyed information is much more that just "Peter bought a car". What is said, in such a simple "X action Y" sentence, is:

1 - "there are entities", and among Entities 1.1-"there are people", 1.2.- "there are things", and 1.3.-"Entities that are not people or things", among people, 1.1.1 -" there is Peter", 1.1.2 -"there are other persons than Peter", among things,1.2.1- there are things that people can buy" and 1.2.2- "things that people cannot buy", among things that people can buy, 1.2.1.1- "there are cars", and 1.2.1.2 – "there are other things than cars", among cars, 1.2.1.1.1 "there is the car Peter bought" and 1.2.1.1.2-"the other cars Peter did not bought." From such a "X action Y" sentence, we can disagree at different levels: "such things, as X and Y, do not exist" (1), "X cannot action Y" (1.2.1), "the Y that was acted by x, was not y" (1.2.1.1.1), and so on.

We can disagree if we think that the category at a given level is not valid, and all the subordinate categories as well. Thus, if A is not valid, the complementary category should be valid and is provided by the network. We advocate that counterfactuals are provided the same ways.

Note that procedures for decision making operate on existing objects in databases that are usually related to some kind of functions. For instance, there are people that can be contacted by loan companies because they get high salary and live in big cities or because they are farmers living in the countryside that need funds for a while. Thus people living in big cities might be asked if they get high salary while people living in the countryside might be asked if they get a farm. First step for having insight is to generate counterfactuals that are "farmers in big cities" and "people in the countryside having high salary". Note that no one can say at this stage if such persons exist in real. This is why counterfactuals are related to creativity. Second step is questioning about what can be "a farmer in big cities" (for instance people who renovate apartments to sell them) and what can be a person with high salary in the countryside (for instance people that rent farms). Third step is to evaluate how much the insight is an operational idea using contextual graphs.

IV. Contextual Graphs

A Contextual Graph (CxG) is a context-based representation of a procedure. CxGs are oriented without circuits, with exactly one input and one output, and a general structure of spindle. A path (from the input to the output of the graph) represents a practice (or a procedure), a type of execution of the task with the application of selected methods. There areas many paths as practices Different solutions can be associated with the unique output, like in the following example chosen in information retrieval: abandon, copy, or save a page before to close the window, but all of them lead to the same conclusion: end of the exploration of the page. A CxG is an acyclic graph because user's tasks are generally in ordered sequences. For example, the activity "Make the train empty of travelers" is always considered at the beginning of an incident solving on a subway line, never at the end of the incident solving. A more drastic divergence in the type of output (e.g. the execution of the task is stopped like "Error 104" in information retrieval) must be considered at a upper level in which the CxG at hand is a branch of an alternative (a contextual element such as "Are the conditions required for the task execution present? If yes go to the CxG otherwise does not consider this contextual graph).

Elements of a Contextual Graph are actions, contextual elements, sub-graphs, activities and parallel action groupings [1]. The action is the elementary task. A contextual element is a pair of nodes, namely a contextual node (1, N) and a recombination node (N, 1) where N is the number of instances of the contextual element considered on different practices. A sub-graph is itself a CxG, and the activity is a particular type of sub-graph identified by human actors as a recurrent structure in CxGs. The parallel action grouping expresses the fact that several groups of actions must be accomplished but that the order in which action groups must be considered is not important, or even could be done in parallel, but all actions must be accomplished before to continue. This is a kind of complex contextual element; such as an activity is a complex action.

V. The role of context in decision making

Context plays an important role since a long time in domains where reasoning, such as understanding, interpretation, anticipation, diagnosis, and decision-making etc., intervenes. This cognitive activity relies heavily on a background or experience that is generally not explicit because made of the specific contextual dimensions of knowledge and activity. In this paper, we present Contextual Categorization and Contextual Graphs (CxGs) [2, 1] that are used in several domains such as medicine, ergonomics, psychology, army, information retrieval, computer security, road safety, etc. The common factor in all these domains is that reasoning is established through procedures that are adapted by actors that take into account the context to create practices as contextualization of the procedures. The example of the coffee preparation in the previous section shows this point.

First, we state that context is always relative to something: context of the reasoning, context of an action, context of an object, etc., something that we call "focus." Second, we cannot speak of context out of its context. Context surrounds its focus and gives meaning to items related to this focus. The context guides the focus of attention, i.e. the subset of common ground that is pertinent to the current task. Indeed, context acts more on the relationships between items in the focus than on items themselves, modifying their extension and surface.

As a consequence, the context makes the focus explicit and conversely, the focus defines the relevant pieces in the context. On the one hand, the focus determines what must be contextual knowledge and external knowledge at a given step. For example, a focus on software development implies contextual knowledge such as the programming language, the constitution of the designer team, etc., i.e. knowledge that could eventually be used when the focus evolves. Some knowledge from the designers' individual context could also be considered such as a previous experience with a given piece of software. On the other hand, the context constrains what must be done in the current focus. This could correspond to the choice of a specific method at a given step of a task of programming the software. A software programmer will focus his/her programming activity in defining classes and methods when in an object-oriented project, but modules and functions if the project uses the functional paradigm. Indeed, some contextual elements are considered explicitly, say for the selection ofthe method and thus can be considered as a part of the way in which the problem is solved atthe considered step.

For a given focus, [1] consider context as the sum of three types of knowledge. First, there is the part of the context that is relevant at this step of the decision-making, and the part that is not relevant. The latter part is called external knowledge. External knowledge appears in different sources, such as the knowledge known by the actor but let implicit with respect to the current focus, the knowledge unknown to the actor (out of his competence), contextual knowledge of other actors in a team, etc. The former part is called contextual knowledge, and obviously depends on the actor and on the decision at hand. Here, the focus acts as a discriminating factor between the external and contextual knowledge. However, the frontier between external and contextual knowledge is porous and evolves with the progress of the focus.

Second, a subset of the contextual knowledge is proceduralized for addressing the current focus. We call it the proceduralized context. The proceduralized context (PC) is a part of the contextual knowledge that is invoked, assembled, organized, structured and situated according to the given focus and is common to the various people involved in decision making.

The triple aspect —context growth by integration of external knowledge in the PC building, by integration of a new "chunk of knowledge" in the contextual knowledge, and context change by the movement between the body of contextual knowledge and proceduralized contexts— gives a dynamic dimension to context [1]. This dynamic component is generally not considered in the literature and explains why making context explicit in an application is a difficult task, except if we restrict context at what can be obtained by sensors like in context-aware applications.

VI. Clarity, rationality and creativity for DSSs

CxGs improves both clarity and rationality for task performance by providing a uniform representation of elements of decision and contexts. For example, how could a sentence be a scientific proposition if it is not written? Writing is a way for increasing clarity and rationality. Consider people that are witnesses of a same visual scene of objects moving or of persons acting. It seems difficult to improve clarity and rationality about actions when they get different interpretations of what happened. Observers of a given visual scene (say, a man running away from a dead body) may not share the same understanding (looking for help vs. fleeing after the murder) and thus have a different ontological commitment (already knowing or not who is the murderer) [8, 20]. Similarly, creativity is of a different ontological commitment from previous thinking and much of evaluation is how much new insight-based procedure could be compatible with existing data and procedures. Success of integration of insight-based procedure into existing CxGs is the evaluation test by modelling the insight-based procedure in two steps: (1) Are the conditions required for the insight-based procedure present? If yes include the CxG, otherwise does not consider this contextual graph and reject Insight. (2) Compare CxGs with and without the insight-based procedure.

For sharing ontological commitments about insights, grammars are useful, but limited, tools. A first, although general, limit is that clarity and rationality about innovation depend on the chosen formalism. For example, an insight could be of a continuous process that is hard to fully capture with binary variables (clarity) and that have unseen super ordinate goals that it is hard to describe and to talk about (rationality). Second, although understanding is context dependent, much of the formalisms for representing and expressing actions do not take context into account.

As discussed previously, we have to consider jointly a new procedure and its context. Thus, one way to share the same ontological commitment is to share the same context. Context has a lot of cognitive effects: it helps memorizing, it helps decision-making and, importantly, it helps understanding. For instance, two persons may disagree about how to perform a task (i.e. the choice between the old and the new method to accomplish the task) simply because they consider two different contexts. Letting implicit the contexts they consider, the persons will have difficulty for negotiating their respective position. CxGs make context explicit and allow to present what is encapsulated in a given procedure. Thus, CxGs render explicit new ideas and help also comparing new and old procedures and find where they differ and why providing clarity and rationality.

Last but not least, if language is understood by generalization, action must be understood by particularization. Let's suppose someone tells us that "*s/he is going from X to Y using Z*". Even if we don't know what X, Y and Z are, we understand by generalization that "*s/he is moving from place X to place Y with the mean of Z*". Although such an understanding is often sufficient in our daily life, it is in no way useful is we are asked "*to go from X to Y using Z*". We precisely needs to know what "X, Y and Z are". Given that "X, Y and Z" are situated in the environment, we need to know the context that makes the novel procedure possible to perform.

CxGs offer such clarity and rationally for understanding how to plan actions, mainly in the design of Human-Machine Interaction

- by representing at the same level elements of reasoning and of contexts, this improves explanation generation,
- by introducing activity such as "chunk of actions" in the representation,
- by context refinement when adding new contextual elements as a new practice is learnt, and by introducing a new instantiation of an existing contextual element,
- by exhibiting the movement of contextual elements between the contextual knowledge and the proceduralized context,
- by tracing how memory (i.e. the storage of contextual knowledge) is structured by chunks of contextual knowledge, knowing the basic contextual elements and their relationships.

VII. Conclusion

In our model, creativity and innovation arises from the flux of contextual elements between these contexts considering counterfactuals realization in the context at hand. The literature often distinguishes two types of context: (1) the "local" context that is close of the focus of attention and highly detailed, and (2) the "distant" context that is general (with less details).For example, van Dijk [17] presents such a position with a local context (called situation),and a global or macro context, defined in terms of higher level. We present a different (but compatible view) by considering that there are different contexts at different levels. This is different from the view of Campbell and Goodman [5] for example (and Hendrix, [9] for semantic networks) that consider context as a way to partition a graph. In short, we think that CxGs formalism is an epistemic tool that provides more clarity and rationality for creativity that we model as creation of counterfactuals: a pathway to clarity, rationality and creativity for Decision Support Systems. The model could be applied to innovative solutions for the future of Air traffic.

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Preventing Interferences between Air Traffic Controller and Future Ground Automation from a Control Theory Approach

Eri Itoh and Vu Duong

Abstract— **Automation has been considered as one approach to assist human decision making as well as to increase the capacity of air traffic. One idea that recently attracts most interests is the concept of "subliminal control," from which an automation system assesses the traffic to remove the potential conflicts that can be easily resolved by simply adjusting subliminal air speed. The removal of these potential conflicts is performed by automatically requesting for changes of speed, using data-link messages from the automation system on the ground to the flight management system on board, all without any human intervention. Current development of this concept assumes that interferences between automation system and air traffic controllers can be avoided. The work presented in this paper deals with the analysis of the future system to detect and resolve the occurrences of interferences, if there is any. We suggest the use of dynamics of aircraft and flight control system to analyze the impacts on the future automation system from a human-machine interaction perspective: Based on the control theory, we mimic the situations that both human air traffic controller and ground automation simultaneously give instructions to the air in order to manage the aircraft with different strategies, and we simulate the aircraft movement by using the rigid-body aircraft model. Analytical results obtained from our simulations show that there exist interferences that disturb navigation parameters and can have safety related consequences. From the findings, we propose a new automation design concept, so-called "Arbitrating System" that automatically adjusts the control authorities of air traffic controller and automation system. Numerical results showed that all interferences can be resolved to ensure safe navigation in this "arbitrating subliminal control" system.**

***Index Terms*— man-machine interface, subliminal control, ground automation**

I. INTRODUCTION

AUTOMATION has been considered as one of the means to achieve better capacity in air traffic control[1][2]. Several investigations on different levels of automation, from automated decision aids to full automation, have been undertaken since the 80's. One of the ideas that attract most interest recently is named "subliminal control"[3][4], from which automated system assesses the traffic to remove conflicts by automatically requests for changes of speeds or climb rate without intervention of human air traffic controller(ATCo). These future ground automation system creates control signals on the ground and send them directory to Flight Management System (FMS) via data-link. Since the ground automation has the potential not to address the emergent situation in an early phase of development, ATCo needs to get back the authority to manage air traffic and interfere in the automation control. The ground automation has been investigating and aiming at its practical use in the next generation Air Traffic Management (ATM) system, however, the impacts caused to ATCos and/or pilots who will be working with the future automation have not been analyzed and discussed yet.

The automatic systems equipped in current aircrafts have remained the potential for errors, induced by the eventual confusion in man-machine interactions. Pilots tend to be confused about unforeseeable behavior of automated aircrafts when responding to an abnormal situation and such confusions could trigger disasters [5][6]. For example, an autopilot sometimes creates confusions in pilot's cognitive and decision-making process and interferes with pilot's duties of basic airmanship. In emergency situation, or when pilots cannot predict behaviors of autopilot, pilots have to disconnect autopilot and shift to manual control. However, it is difficult to decide whether or not they must switch off autopilot since pilots have to understand behaviors of the autopilots. Feedback control with actuator limiting is related to pilot-induced oscillation (PIO)[7][8] , which show that human-friendly automation must be designed considering analyzed impacts of safety issues in human-machine interaction.

With learning from conflicts between pilot and automation in the past, this paper discusses the future ground automation from the perspective of human-machine interaction: Firstly, to analyze the impacts of the ground automation, we suggest the use of dynamics of aircraft and flight control system. Based on the control theory, we mimic the situation in the case that both ATCo and ground automation give instructions to FMS in order to manage the aircraft with different strategies and simulate the aircraft movement by using the rigid-body aircraft model. We propose a new automation design concept integrating ground automation, ATCo, and pilot to avoid automation interferences. The effectiveness of the method is confirmed via numerical

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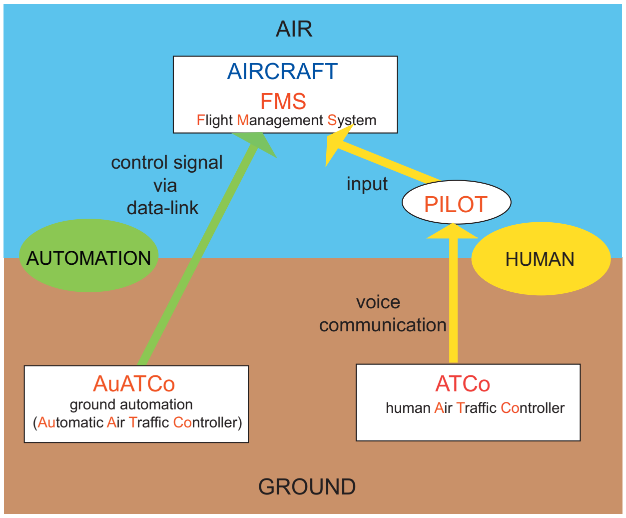

Fig.1 Future ATM system

simulation.

II. INTERFERENCES BETWEEN HUMAN AND AUTOMATION IN THE FUTURE AIR TRAAFFIC MANAGEMENT

A. *Issues in the Control Loop Future ATM system*

Figure 1 shows the future ATM system in which human beings (ATCos and pilots) and the ground automation (Automatic Air Traffic Controller: AuATCo) are working together in the same control loop. In current ATM, information such as climbing and descending ratios, turning direction and speed etc., flows between ATCo and pilot through voice communication. Pilot operates autopilot and other automation settings in order to keep aircraft following ATCo instructions safely. Pilot shifts on manual control if the automation equipped with the aircraft cannot works well under unpredictable and urgent conditions, for example, under strong atmospheric turbulence and/or when some parts of the aircraft failed to function properly. In the future ATM automation concept, additional information flows between AuATCo and FMS. Information, for example, flight plans, real time flight data and the target value of speed control etc, is shared between them. The problem comes from the fact that there is no information flow between ATCo and AuATCo. Because ATCo and AuATCo do not share the same information to each other, it is considered that there are interferences between human beings and automation when the control authorities are not determined according to traffic situations.

The authors consider the situation where AuATCo and ATCo simultaneously give control commands to aircrafts with different strategies to manage air traffic. For example, AuATCo gives speed commands to the aircraft to resolve conflicts in the air, while ATCo gives climb/descent commands to decongest the airspace. In the concept of subliminal control, ATCo does not sense how the AuATCo is working, so there are possibilities that ATCo gives altitude command to the same aircraft via pilot. The ATCo command is given to the air through voice communication, so AuATCo does not sense the intent of ATCo. In this case, how do the commands interfere in each other and influence aircraft navigation? We conduct numerical simulations which mimic situations which cause interferences between ATCo (via pilot), AuATCo, and aircraft under a control theory based model detailed in Section II.B. On the purpose to analyze the impacts of interferences between ATCo (via pilot) and AuATCo, we suggest the use of aircraft dynamics and control theory.

B. *Problem Formulation*

1) *Aircraft Dynamics*

Based on Ref. [9], nonlinear dynamics of a B747-100 flying at 40,000 ft are utilized in this simulation. In order to simplify the simulation, we focused on the longitudinal movement of the aircraft. Altitude h, airspeed V, airspeed following x direction of the body axis u, airspeed following z direction of the body axis w, pitch angle θ and pitch angle velocity q are calculated by using the equations[10] in the appendix.

2) *Autopilot Design*

We design autopilots which control longitudinal flight path (altitude) and airspeed using Total Energy Control System (TECS)[11]. The elevator command δ_{ec} and thrust command δ_{Tc} are computed based on total energy demand arising from both flight path and speed targets as shown in the following equations:

$$\delta_{ec} = \left(K_{EP} + K_{EI}/s\right)\left(\dot{V}_{\varepsilon}/g - \gamma_{\varepsilon}\right) + damping \quad (1)$$

$$\delta_{Tc} = \left(K_{TP} + K_{TI}/s\right)\left(\gamma_{\varepsilon} + \dot{V}_{\varepsilon}/g\right) \quad (2)$$

The gain relationships are described as follows:

$$K_{TP} = K_{EP} = 1.0 \quad (3)$$

$$K_{TI} = K_{EI} \quad (4)$$

The damping terms in Eq. (1) consists of the feedbacks (i.e., pitch rate) that are necessary to stabilize the short period pitch dynamics are shown as follows:

$$damping = K_{\ddot{h}}\ddot{h} + K_q q \quad (5)$$

The error of flight angle γ_{ε} and the error of acceleration along the path $\dot{V}_{\varepsilon}$ are described as follows:

$$\begin{aligned}\gamma_{\varepsilon} &= \gamma_c - \gamma = \dot{h}_c/V - \dot{h}/V \\ &= K_h h_{\varepsilon}/V - \dot{h}/V = K_h\left(h_c - h\right)/V - \dot{h}/V\end{aligned} \quad (6)$$

$$\dot{V}_{\varepsilon} = \dot{V}_c - \dot{V} = K_V V_{\varepsilon} - \dot{V} = K_V\left(V_c - V\right) - \dot{V} \quad (7)$$

3) Engine Model

As an engine model, this paper applies 1 dimensional transfer function defined as follows.

$$T = \frac{K_p}{1 + \tau_p s} \delta_{Tc} \quad (8)$$

Where

$$\tau_p = 3.5 \,,\; K_p = 40000.$$

We set maximum values of thrust as $60403.59 \ (slug \cdot ft / s^2)$ which is increased thrust value of steady flight by 10 %.

4) Pilot Model

As a model which mimics manual control of pilot, this paper uses the following 2 dimensional transfer function.

$$Y_p(s) = \frac{\omega_p{}^2}{s^2 + 2\xi_p \omega_p s + \omega_p{}^2} \quad (9)$$

Where $\omega_p = 0.3$ and $\xi_p = 0.8$. This model mimics elevator control of a pilot who controls elevator angle deliberately not to induce short-period oscillation of the aircraft flying at the high altitude.

C. Results of Impact Analysis

We give following 3 scenarios to mimic situations of interferences between ATCo (via pilot) and AuATCo. Scenario 1 and 2 simulate situations where ATCo and AuATCo give different control commands to autopilot equipped with the aircraft. Scenario 3 simulates impacts when a pilot manually controls aircraft to navigate the aircraft following ATCo's instruction while AuATCo gives a different control command. AuATCo gives speed command to change small amount of airspeed of which en-route ATCo do not sense how AuATCo works on a display screen.

1) Scenario 1

Scenario 1 consists of following 3 processes.

Process 1: ATCo gives a command to descend altitude by 1,000 ft, 2,000ft, 3,000ft, and 4,000ft while keeping the airspeed.

Process 2: The pilot inputs the ATCo's instruction to FMS. FMS selects an autopilot to control altitude.

Process 3: AuATCo gives a command to decrease airspeed by 5 ft/s.In the altitude controller, gain values in the damping term in Eq. (5) are $K_{\ddot{h}} = 0.001151$ and $K_q = 0.075$.

Performance of the altitude controller where the target altitude h_c is 39,000 ft, 38,000 ft, 37,000 ft, and 36,000 ft while keeping the current airspeed 867.8 ft/s is shown in Figs. 2 and 3. As shown in Figs. 2 and 3, the designed altitude controller works to achieve the target altitude while keeping the airspeed. Fig. 4 shows vertical acceleration of which the altitude controller achieves.

Next, we simulate interferences after AuATCo gives airspeed command V_c which reduces airspeed by 5 ft/s. Figs. 5 to 7 show the results of the interferences between ATCo and AuATCo when AuATCo command overrides the target airspeed during the flight. Comparing with Figs. 4 and Fig. 7, change of vertical acceleration is increased by around 50 % when ATCo and AuATCo are acting together than the case that AuATCo is acting alone.

2) Scenario 2

Scenario 2 consists of following processes.

Process 1: AuATCo gives command to decrease airspeed by 5 ft/s while keeping the altitude. FMS selects an autopilot to control airspeed.

Process 2: ATCo gives command to descend altitude by 1,000 ft, 2,000ft, 3,000ft, and 4,000ft while keeping the airspeed. Pilot inputs the ATCo instruction to FMS.

Process 3: AuATCo continuously gives the speed command till the airspeed is decreased by 5ft/s.

In the speed controller, gain values in the damping term in Eq. (5) are $K_{\ddot{h}} = 0.01036$ and $K_q = 0.075$. Performance of the speed controller where it works to reduce airspeed by 5 ft/s while keeping the altitude is shown in Figs. 8 and 9.

Next, we simulate interferences when ATCo gives altitude command h_c which reduces altitude to 39,000 ft, 38,000ft, 37,000ft, and 36,000 ft. Figs. 10 and 11 show the results of the interference between ATCo and AuATCo These results show that interferences of AuATCo and ATCo disturb not only navigating the aircraft following the AuATCo and ATCo instruction but also inducing long-term oscillation. The results show the impact of the oscillation when AuATCo and ATCo simultaneously give different commands to the autopilot. Flight control system (autopilot) uses feedback gain as shown in the damping term in Eq. (5) to stabilize aircraft movement. For example, such it works to controlling aircraft under small change of vertical acceleration. However, oscillation is induced since the feedback gains are not suitable to controlling altitude.

3) Scenario 3

Scenario 3 consists of following processes.

Process 1: ATCo gives command to decrease altitude by 1,000ft.

Process 2: Pilot manually controls elevator angle to navigate the aircraft following the ATCo instruction.

Process 3: AuATCo gives control command to decrease airspeed by 5ft/s. An autopilot controls the airspeed to achieve the AuATCo instruction.

A pilot model is utilized as described in Eq. (9). Figs. 12 to 14 show the aircraft movement when the pilot controls elevator angle to reduce altitude from 40,000 ft to 39,000 ft. Because the pilot model doesn't combine thrust control, long term oscillation is caused in airspeed as shown in Fig. 13.

By using the pilot model and the designed speed controller, interferences between AuATCo and ATCo via pilot are

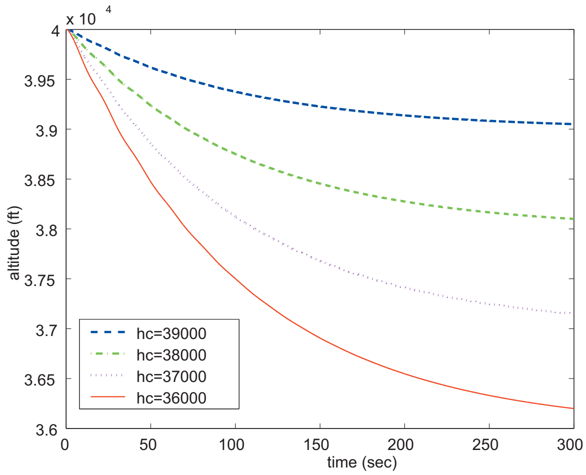

Fig. 2 Performance of an autopilot which controls altitude : altitude

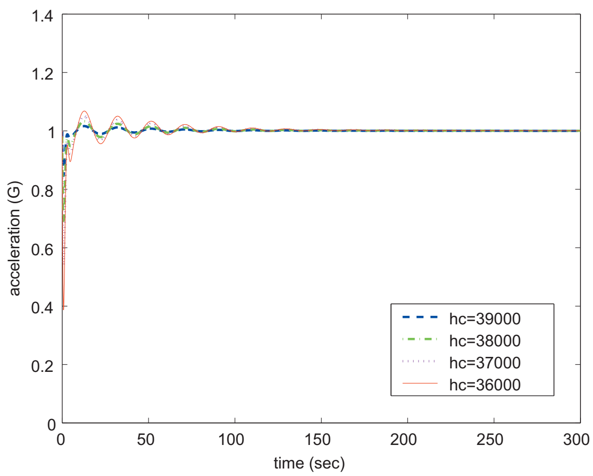

Fig. 4a Performance of an autopilot which controls altitude: vertical acceleration (300 seconds simulation)

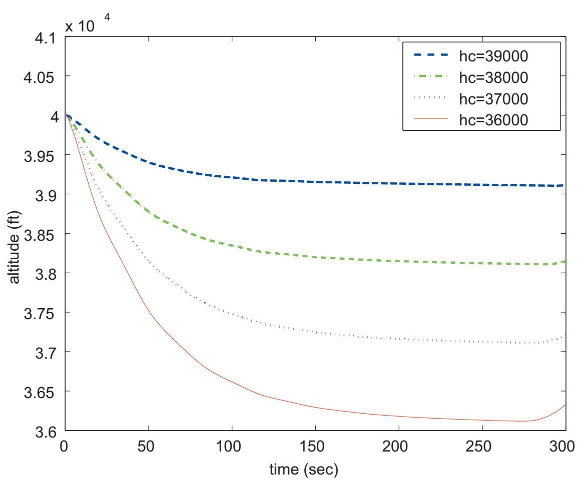

Fig. 5 Interference simulated in scenario 1: altitude

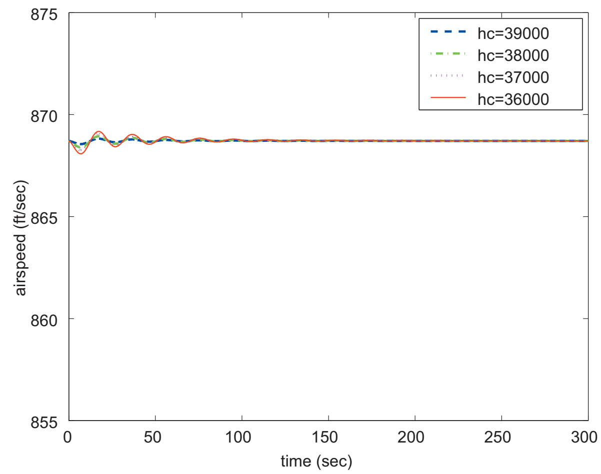

Fig. 3 Performance of an autopilot which controls altitude: airspeed

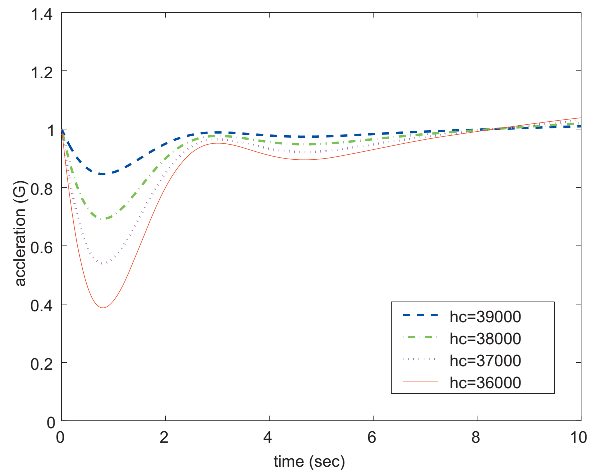

Fig. 4b Performance of an autopilot which controls altitude: vertical acceleration (10 seconds simulation)

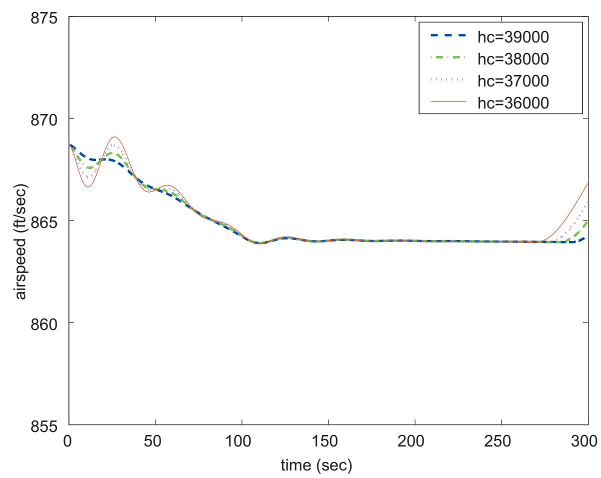

Fig. 6 Interference simulated in scenario 1: airspeed

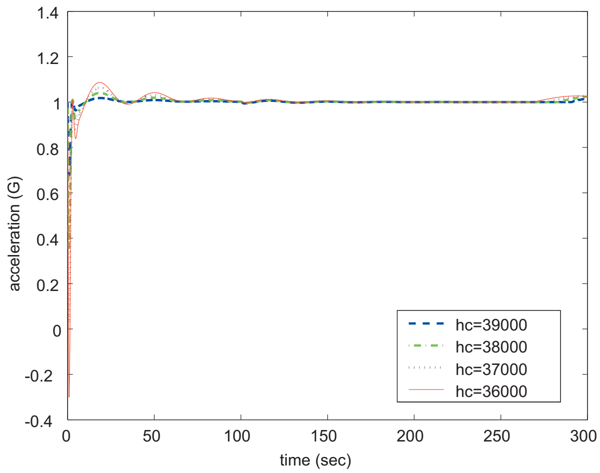

Fig. 7a Interference simulated in scenario 1: vertical acceleration (300 seconds simulation)

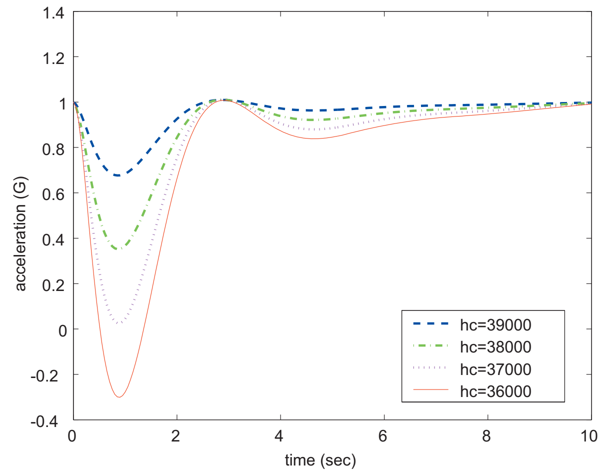

Fig. 7a Interference simulated in scenario 1: vertical acceleration (10 seconds simulation)

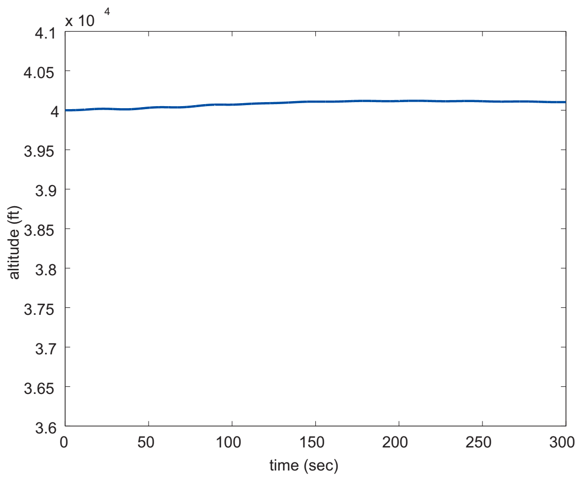

Fig. 8 Performance of an autopilot which controls airspeed : altitude

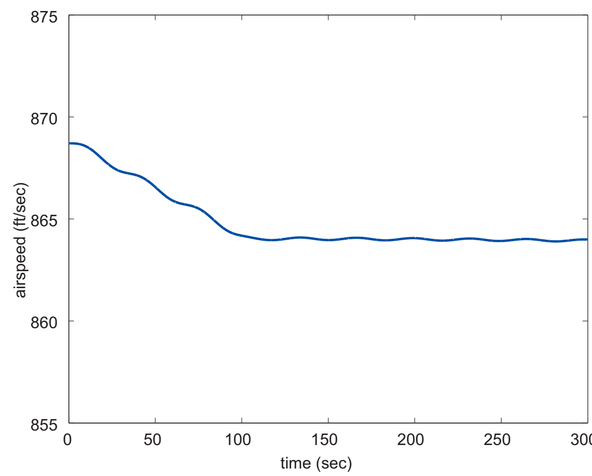

Fig. 9 Performance of an autopilot which controls airspeed: airspeed

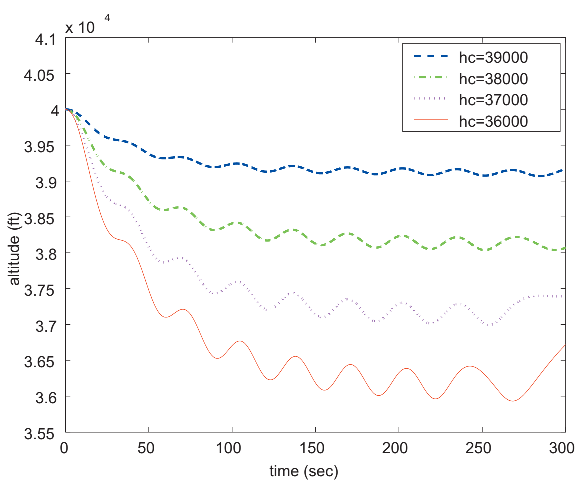

Fig. 10 Interference simulated in scenario 2: altitude

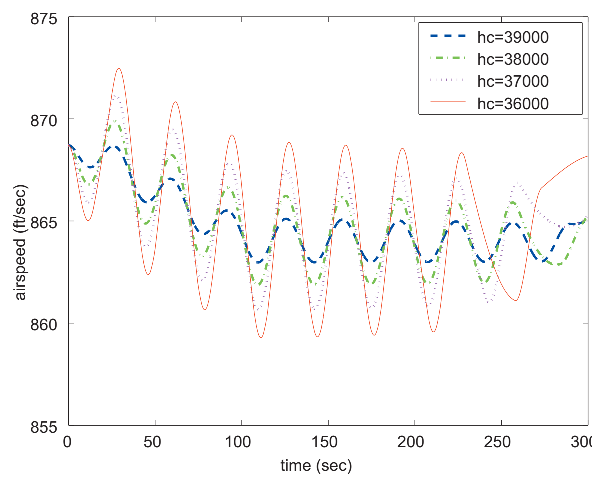

Fig. 11 Interference simulated in scenario 2: airspeed

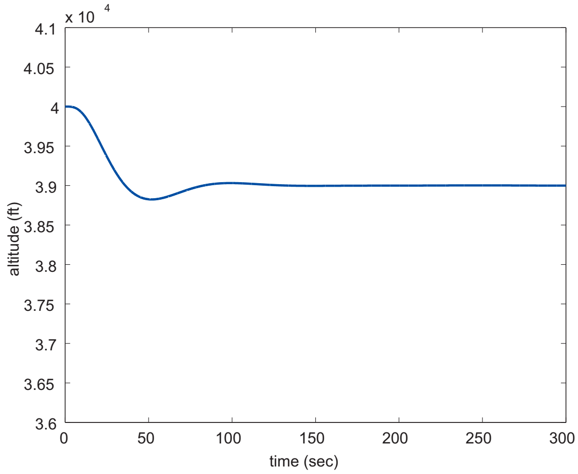

Fig. 12 Performance of a pilot model: altitude

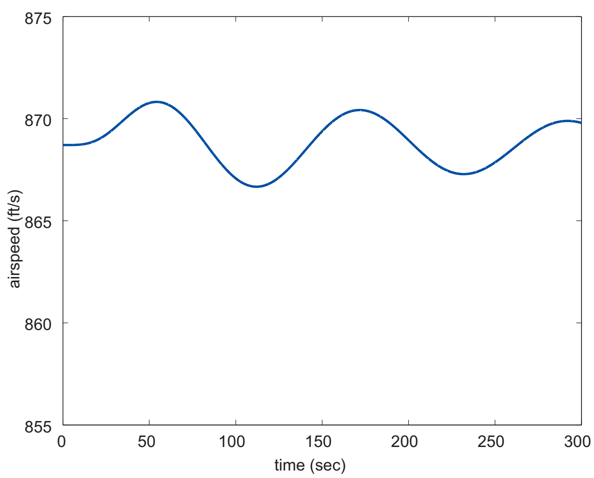

Fig. 13 Performance of a pilot model: airspeed

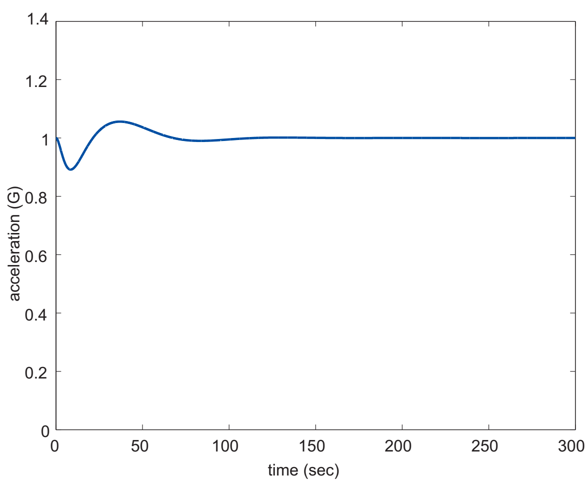

Fig. 14 Performance of a pilot model: vertical acceleration

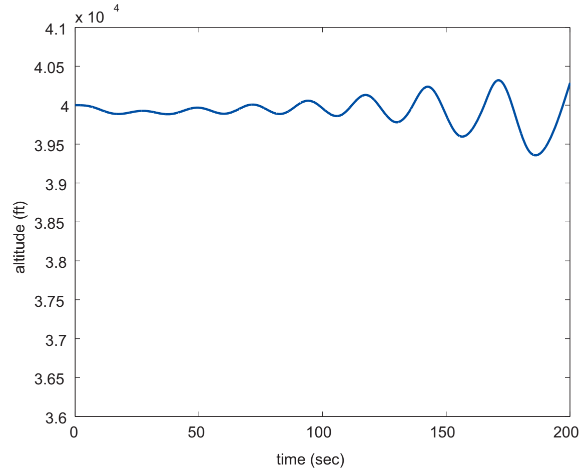

Fig. 15 Interference simulated in scenario 3: altitude

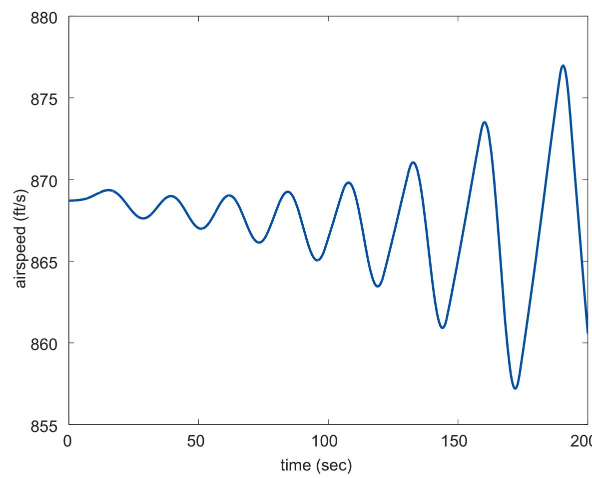

Fig. 16 Interference simulated in scenario 3: airspeed

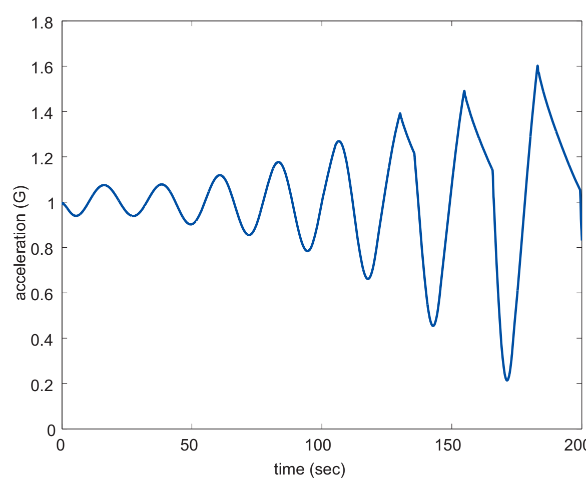

Fig. 17 Interference simulated in scenario 3: vertical acceleration

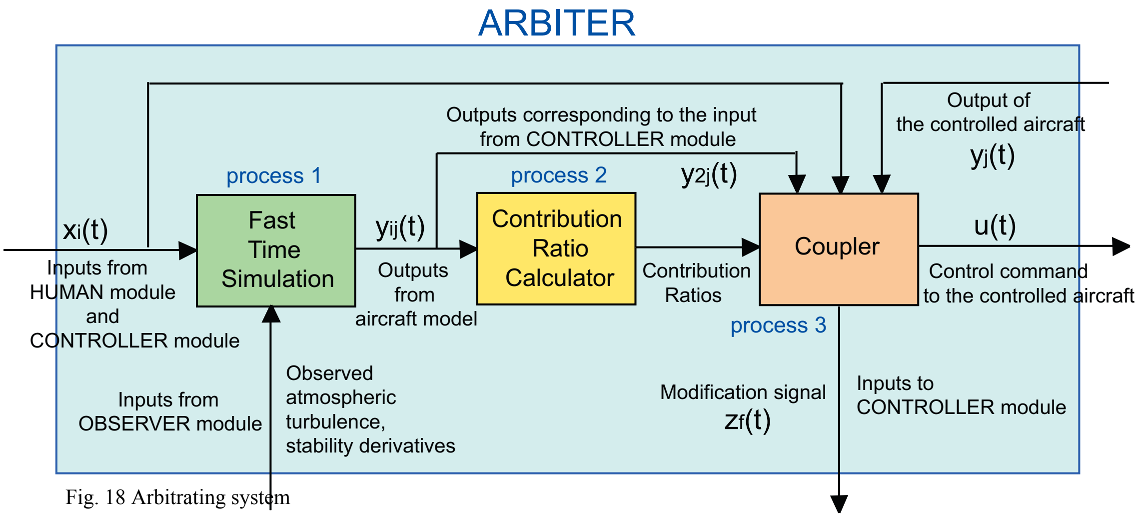

Fig. 18 Arbitrating system

simulated as shown in Figs. 15 to 17. As shown in Figs.15 to 17, the control inputs of AuATCo and ATCo made unstable oscillation. The results indicate that the interferences cause instability of the aircraft movement.

III. PREVENTING INTERFERENCES BETWEEN HUMAN AND AUTOMATION IN THE FUTURE ATM

A. *Arbitrating System*

In order to prevent interferences between AuATCo and ATCo (via pilot), we propose a new system called arbitrating system based on our previous work [12]-[15]. The arbitrating system calculates weights given to the control commands from ATCo (via pilot) and AuATCo, and takes over control authority to resolve interferences. By adaptively adjusting the control authority between automation and human control in FMS, the proposing system contributes to flight safety. Fig. 18 shows the basic mechanism of arbitrating system. The arbitrating system includes 3 main elements: a predictor, contribution ratio calculator, and coupler.

1) *Predictor*

First, the arbitrating system predicts outputs of the aircraft corresponding to control commands of both human (ATCo via pilot) and automation (AuATCo). The arbitrating system possesses the dynamic model of the controlled aircraft and the flight control system including the autopilots within its framework. By using the dynamic model, the outputs $y_{ij}(t)\ \ (i=1,2\ \ j=1,2,\dots l)$ for inputs $x_{ik}(t)\ \ (i=1,2\ \ k=1,2,\dots p)$ to the aircraft are numerically simulated. l corresponds to the number of outputs from the aircraft model that are used to calculate the contribution ratios in a contribution ratio calculator. p corresponds to the number of inputs from human (ATCo) and automatic system (AuATCo). In this simulation, we utilize elevator input and thrust input, so we set $p=2$. The values of $y_{1j}(t)$ correspond to the outputs when the control commands $x_{1k}(t)$ are input to the aircraft model from ATCo via pilot. The values of $y_{2j}(t)$ correspond to the outputs when the control commands $x_{2k}(t)$ are input to the aircraft model from AuATCo.

2) *Contribution Ratio Calculator*

Second, contribution ratios $\lambda_i(t)\ \ (i=1,2)$ are calculated by using the outputs of the aircraft model simulated in a predictor. $\lambda_1(t)$ is a contribution ratio for ATCo, and $\lambda_2(t)$ is for AuATCo. The contribution ratio represents the extent to which each inputs presently accounts for the behavior of the aircraft dynamics.

In order to calculate contribution ratios, first, performances of ATCo and AuATCo are individually quantified. We measure the performances of each control commands based on the following index $E_{ij}(t)\ \ (i=1,2\ \ j=1,2,\dots l)$, which is given by

$$E_{ij}(t)=\frac{\sum_{s=n-m}^{n}\left(\varepsilon_{ij}(t_s)\right)^2 e^{(s-n+m)/m}}{\sum_{s=n-m}^{n} e^{(s-n+m)/m}} \qquad (10)$$

where $\varepsilon_{ij}(t)$ is error values between $y_{ij}(t)$ and target values, which are the desired outputs of the aircrafts at present time t and n is the number of time steps at present time t. In this case, t is equal to t_n. m is the number of time steps of past tracking errors considered in the index.

In order to calculate $\varepsilon_{ij}(t)$ in Eq. (10), flight envelope protection is applied. In this paper, the flight envelope protection implies that the arbitrating system adaptively adjusts the control authority when the human side (ATCo via pilot) does not control the aircraft to satisfy the defined flight envelope; this envelope defines that the range aircraft safely continues its flight. In this paper, the arbitrating system is applied for longitudinal control of the aircraft, so the flight envelope is defined as follows:

$$\begin{aligned}\theta_{\min} &\le \theta_1(t) \le \theta_{\max} \\ \dot{\omega}_{\min} &\le \dot{\omega}_1(t) \le \dot{\omega}_{\max} \\ \ddot{\omega}_{\min} &\le \ddot{\omega}_1(t) \le \ddot{\omega}_{\max}\end{aligned} \quad (11)$$

where $\theta_1(t)$, $\dot{\omega}_1(t)$, and $\ddot{\omega}_1(t)$ are the outputs of the aircraft model corresponding to the input from the ATCo calculated in the arbitrating system. As shown in (11), upper and lower limits are introduced for pitch angle, vertical acceleration, and rate of vertical acceleration. This paper yields $\theta_{\min} = -11(\deg)$, $\theta_{\max} = 11(\deg)$, $\dot{\omega}_{\min} = -1.0(G)$, $\dot{\omega}_{\max} = 2.5(G)$, $\ddot{\omega}_{\min} = -0.3(G/s)$, and $\ddot{\omega}_{\max} = 0.3(G/s)$. Upper and lower values of $\dot{\omega}$ are designated values at which B747-400 flies safely. The limitation of $\ddot{\omega}$ is the rate limitation of vertical acceleration in a speed control mode of an autopilot in the distressed aircraft. $\varepsilon_{ij}(t)$ is defined as follows:

$$\text{If} \quad y_{ij}(t) < y_{j\min},$$

$$\text{then} \quad \varepsilon_{ij}(t) = \frac{y_{ij}(t) - y_{j\min}}{y_{j\min}}. \quad (12)$$

$$\text{If} \quad y_{j\max} < y_{ij}(t),$$

$$\text{then} \quad \varepsilon_{ij}(t) = \frac{y_{j\max} - y_{ij}(t)}{y_{j\max}}. \quad (13)$$

where

$$\begin{aligned} & y_i(t) \quad (i = 1,2) \\ &= \left[y_{ij}(t)\right]^T (j = 1,2,3) \\ &= \left[y_{i1}(t), \quad y_{i2}(t), \quad y_{i3}(t)\right]^T \\ &= \left[\theta_i(t), \quad \dot{\omega}_i(t), \quad \ddot{\omega}_i(t)\right]^T. \end{aligned} \quad (14)$$

$y_1(t)$, the output of the aircraft model, corresponds to the input from ATCo and $y_2(t)$, the output of aircraft model, corresponds to the input from AuATCo.

By using the index as shown in Eq. (10), performances of each command are numerically evaluated. The index (10) measures the performances of each input of ATCo and AuATCo by using value of errors predicted in the past.

The contribution ratios of each module $\lambda_i(t)$ are calculated by using Eq. (10) and soft-max function. The contribution ratios are given as follows:

$$\lambda_i(t) = \frac{\sum_{j=1}^{l} e^{-(E_{ij}(t)/\sigma)}}{\sum_{i=1}^{2} \sum_{j=1}^{l} e^{-(E_{ij}(t)/\sigma)}} \quad (15)$$

where σ is a scaling constant. In this simulation, we set $\sigma = 10.0$. The soft-max function normalizes the tracking errors across the modules so that the contribution ratios lie between 0 and 1 and the sum of the contribution over the modules is 1.

If $\lambda_1(t) = 0.5$ has given for 1 second, $\lambda_i(t_n)$ is calculated as follows:

$$\text{If} \quad \lambda_1(t_{n-1}) < 1.0$$

$$\text{Then} \quad \lambda_1(t_n) = \lambda_1(t_{n-1}) + 0.002e^{(\lambda_1(t_{n-1})-0.5)} \quad (16)$$

$$\lambda_2(t_n) = 1.0 - \lambda_1(t_n) \quad (17)$$

3) Coupler

Third, the control commands from ATCo and AuATCo are adjusted and added in this process. The input from the arbitrating system $u_k(t)$ to the aircraft is given as follows:

$$u_k(t) = \sum_{i=1}^{2} \lambda_i(t) x_{ik}(t) \quad (18)$$

The input of ATCo or AuATCo with a smaller error index than that of the other greatly contributes to input $u_k(t)$. Conversely, the other input has a low contribution to $u_k(t)$.

B. The Effectiveness of the Arbitrating System

In this section, the arbitrating system is applied for 3 scenarios which mimics the interferences between ATCo (via pilot) and AuATCo in the previous chapter. The effectiveness of the arbitrating system will be confirmed through the results of the numerical simulation.

1) Application for Scenario 1

Firstly, the arbitrating system is applied for scenario 1. Figs. 19 to 22 show the effectiveness of the arbitrating system. As shown in Figs. 19 and 20, the arbitrating system works to navigate the aircraft following the ATCo instruction which controls the altitude while keeping the airspeed. As shown in Fig. 21, the arbitrating system works to reduce the change of the vertical acceleration comparing with Fig. 7 As shown in Fig. 22, the arbitrating system reduce the control authority of ATCo and mixes the inputs of ATCo and AuATCo in early stage of the aircraft response in order to reduce the change of the vertical acceleration.

2) Application for Scenario 2

Secondly, the arbitrating system is applied for scenario 2. Comparing with Figs. 10 and 11, Figs. 23 and 24 show that the arbitrating system works to stabilize the long term oscillation even while ATCo and AuATCo are working together. As shown in Fig. 25, in order to reduce the change of vertical acceleration caused by the altitude control, the arbitrating system reduce the control authority of ATCo and mixes the inputs of ATCo and AuATCo in early stage of the aircraft response. After this, the

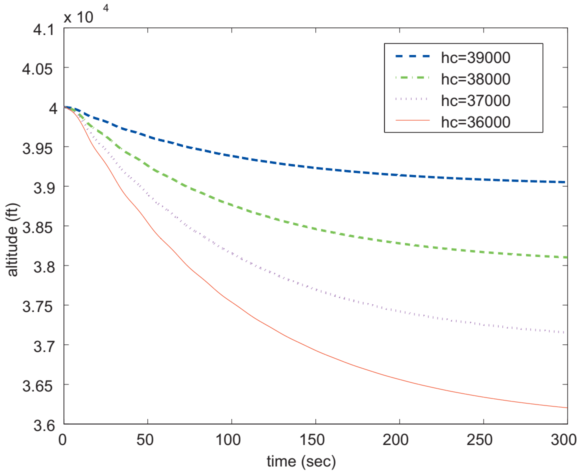

Fig. 19 Application of the arbitrating system for scenario 1 : altitude

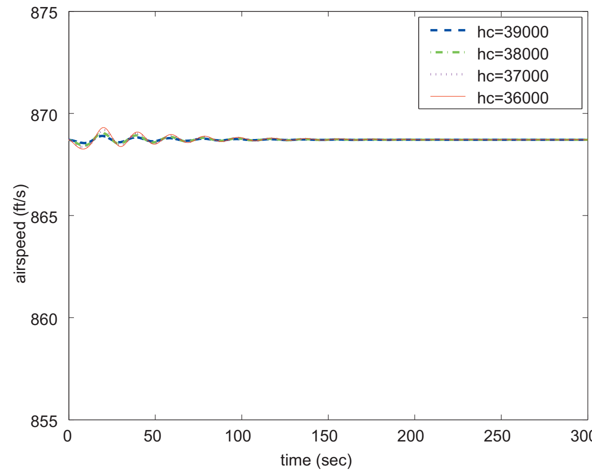

Fig. 20 Application of the arbitrating system for scenario 1: airspeed

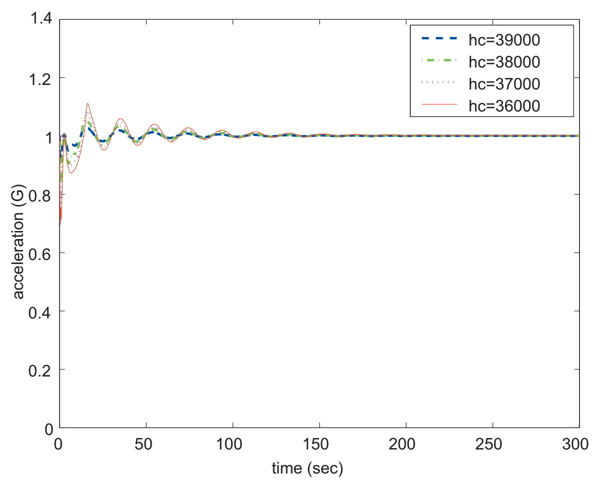

Fig. 21a Application of the arbitrating system for scenario 1: vertical acceleration (300 seconds simulation)

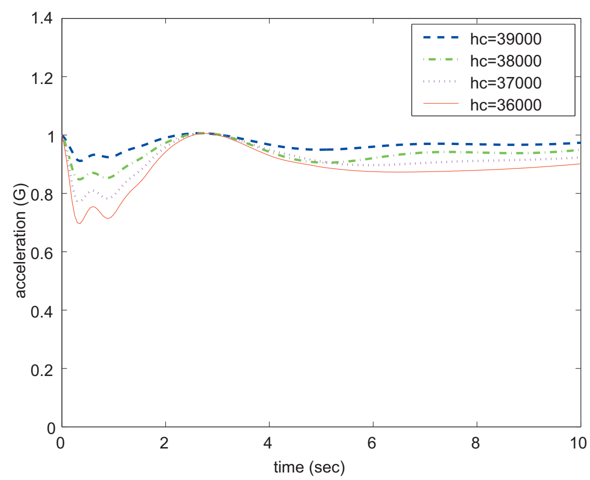

Fig. 21b Application of the arbitrating system for scenario 1: vertical acceleration (10 seconds simulation)

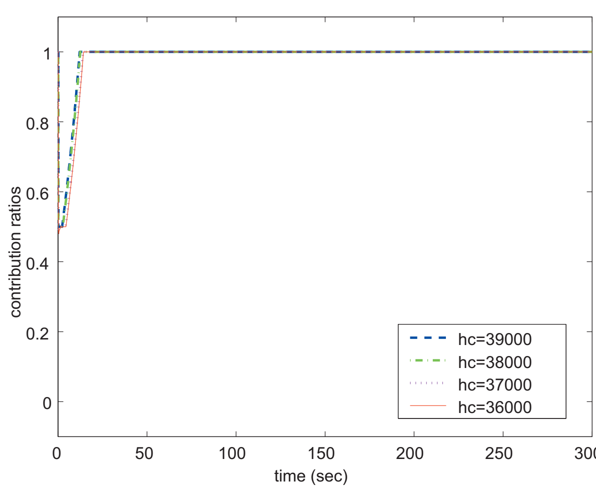

Fig. 22a Application of the arbitrating system for scenario 1: contribution ratio of ATCo

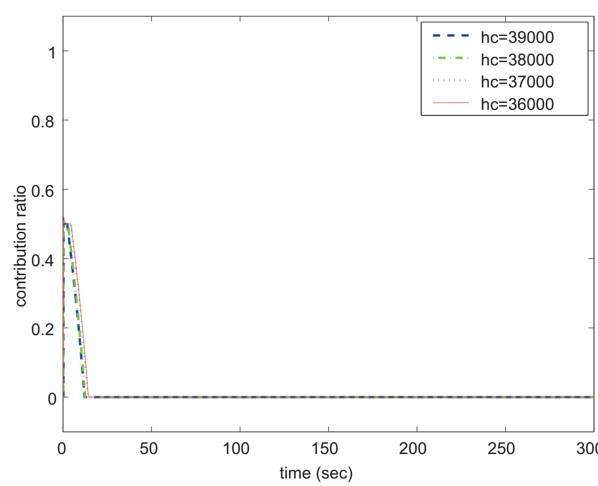

Fig. 22b Application of the arbitrating system for scenario 1: contribution ratio of AuATCo

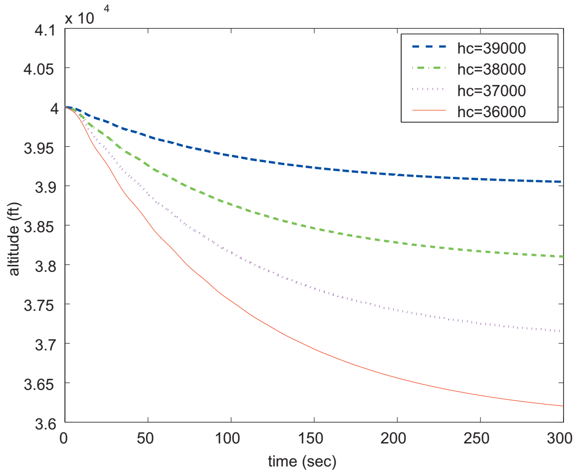

Fig. 23 Application of the arbitrating system for scenario 2 : altitude

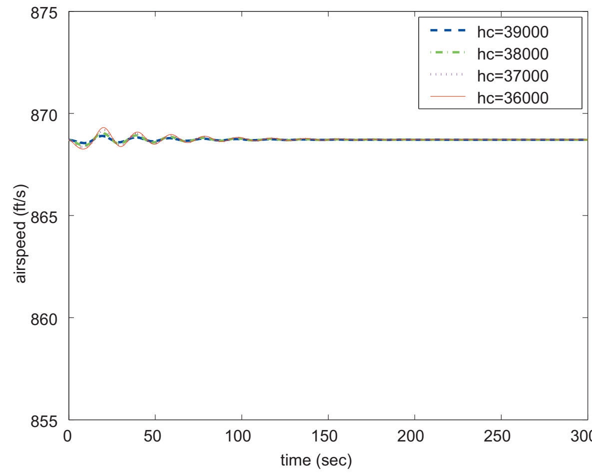

Fig. 24 Application of the arbitrating system for scenario 2: airspeed

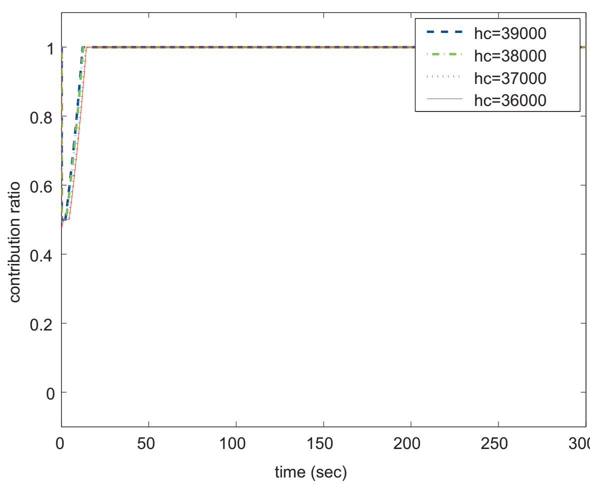

Fig. 25a Application of the arbitrating system for scenario 2: contribution ratio of ATCo.

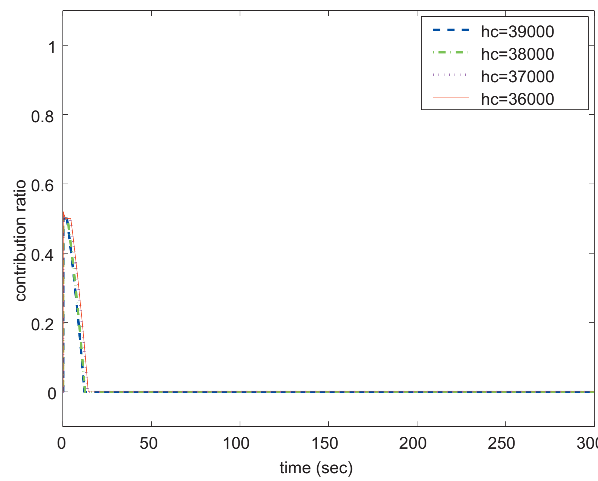

Fig. 25b Application of the arbitrating system for scenario 2: contribution ratio of AuATCo

arbitrating system gives control authority to ATCo. As a result, the aircraft is controlled following the ATCo's instruction as shown in Figs. 23 and 24.

3) Application for Scenario 3

The arbitrating system is applied for scenario 3 which mimics the situation which a pilot manually controls the elevator angle of the aircraft while the AuATCo keeps controlling the airspeed via the autopilot. Figs. 26 to 28 show the aircraft movement the arbitrating system achieved. As shown in Fig. 29, the arbitrating system works to give 100 % of control authority to pilot while the pilot appropriately controls the aircraft as shown in Figs. 12 and 14. As a result, comparing Figs. 15 to 17 and Figs. 26 to 28, it is shown that the arbitrating system works to stabilize the aircraft movement.

4) Application for Pilot Error

In this section, we simulate the situation when the pilot inappropriately controls the aircraft while the autopilot is working to achieve the target airspeed AuATCo instructs. The gain values of the autopilot in the damping term in (13) are $K_{\ddot{h}} = 0.001151$ and $K_q = 0.075$. A pilot model is utilized as described in (25). The parameters in (25) which express the character of pilot control are selected as $\omega_p = 2.0$ and $\xi_p = 0.1$. The pilot model expresses inappropriate elevator control which causes oscillation of the aircraft flying at high altitude. Figs. 30 to 33 show the aircraft movement when the pilot model controls elevator angle to reduce altitude from 40,000 ft to 39,000 ft. As shown in Figs. 30-33, the pilot model controls altitude while inducing longitudinal oscillation.

The arbitrating system is applied to this situation, and simulation results are obtained as shown in Figs. 34 - 38. Comparing Figs. 30 - 33 and Figs. 34 - 37, it is shown that the arbitrating system works to reduce the elevator angle oscillation, and it works to reduce the change of the vertical acceleration. The contribution ratios (Fig. 38) are calculated to reduce the control authority from the human side when the pilot leads instability of the aircraft movement.

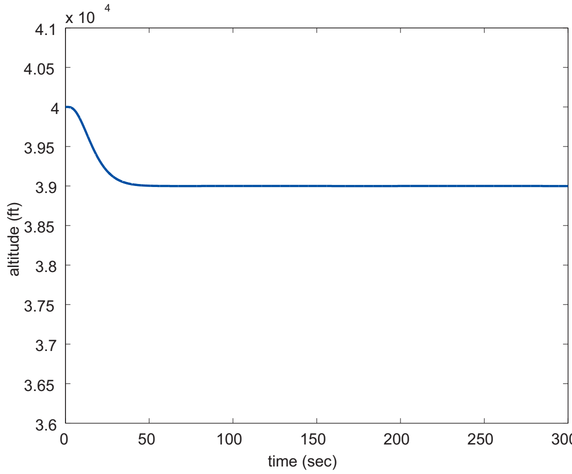

Fig. 26 Application of the arbitrating system for scenario 3 : altitude

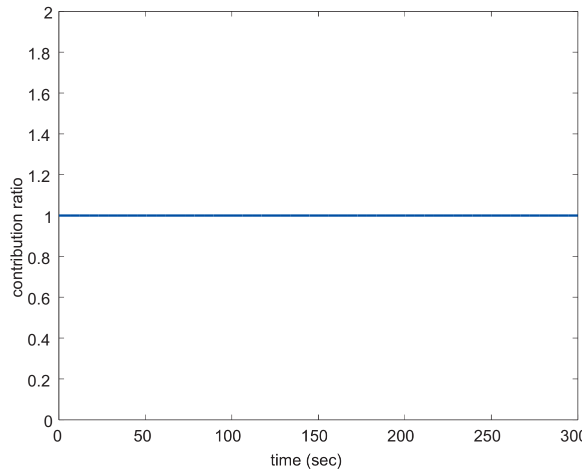

Fig. 29a Application of the arbitrating system for scenario 3: contribution ratio of ATCo

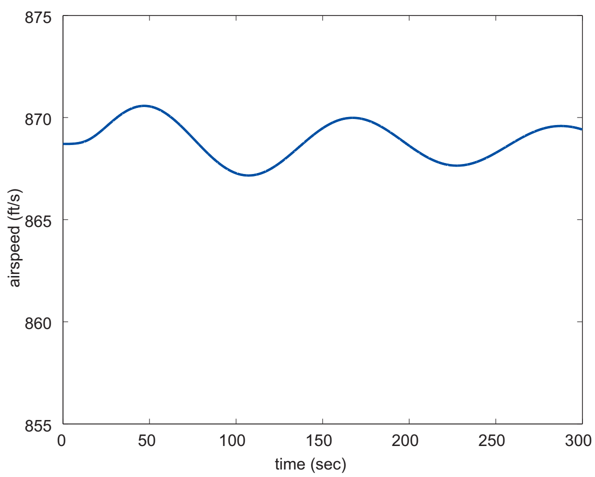

Fig. 27 Application of the arbitrating system for scenario 3: airspeed

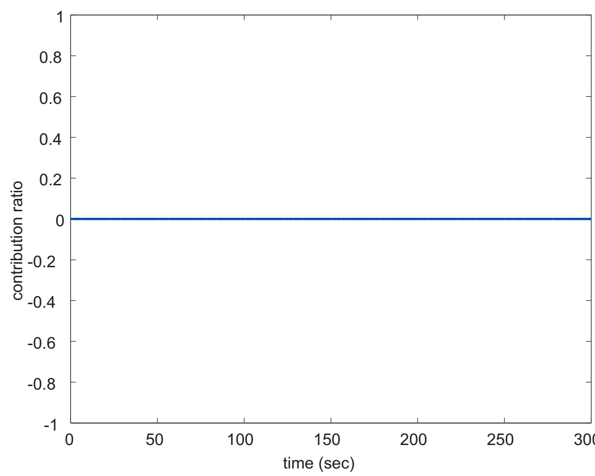

Fig. 29b Application of the arbitrating system for scenario 3: contribution ratio of AuATCo

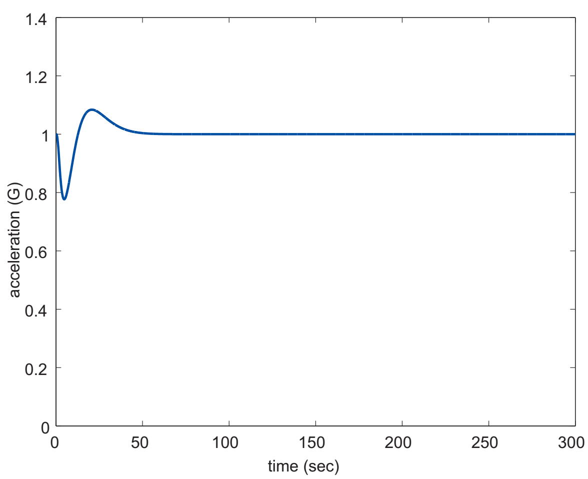

Fig. 28 Application of the arbitrating system for scenario 3: vertical acceleration

IV. BENEFITS OF THE ARBITRATING SYSTEM

The arbitrating system realizes a redundant design consists of human and automation working together in the same control loop. If ATCo inputs control command which safely navigates the aircraft via pilot operation/control, the arbitrating system gives full control authority to the human side (ATCo via pilot). If ATCo and/or pilot give inappropriate control inputs to the aircraft, for example, control inputs which induce oscillation of the pitch angle and the big change of the vertical acceleration, the arbitrating system works to stabilize the aircraft movement by using the control commands from automation system (AuATCo) via contribution ratios. Since the arbitrating system automatically adjust the control authority between ATCo and AuATCo in order to keep safe flight, ATCo and pilot don’t need to disconnect the AuATCo input to the autopilot. In this way, the arbitrating system allows us to realize “arbitrating subliminal control” without interference between ATCo, pilot, and AuATCo and contribute to keep the flight safely.

The other benefit is that the arbitrating system has a simple algorithm and architecture. The simple algorithm allows us to

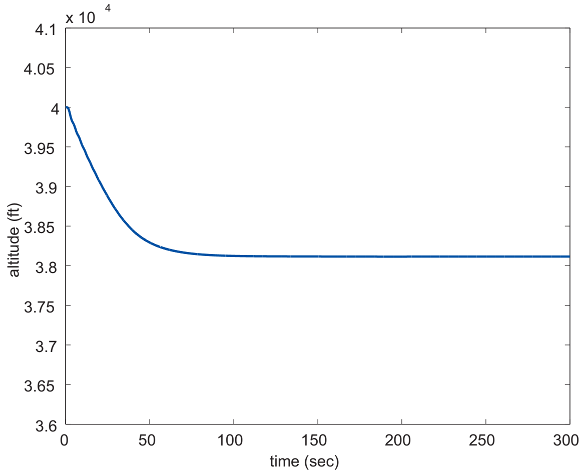

Fig. 30 Performance of the pilot model ($\omega_p = 2.0$, $\xi_p = 0.1$) : altitude

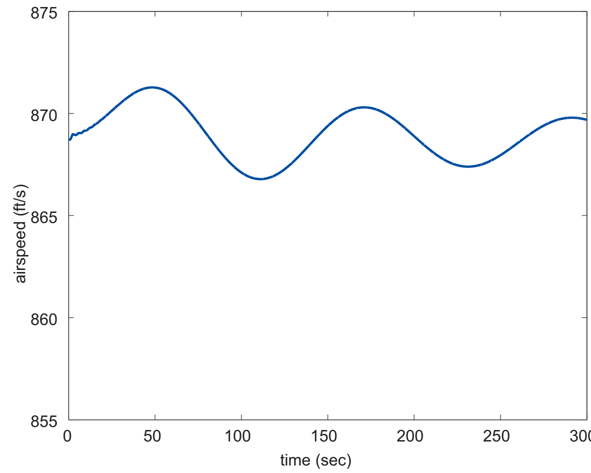

Fig. 31 Performance of the pilot model ($\omega_p = 2.0$, $\xi_p = 0.1$) : airspeed

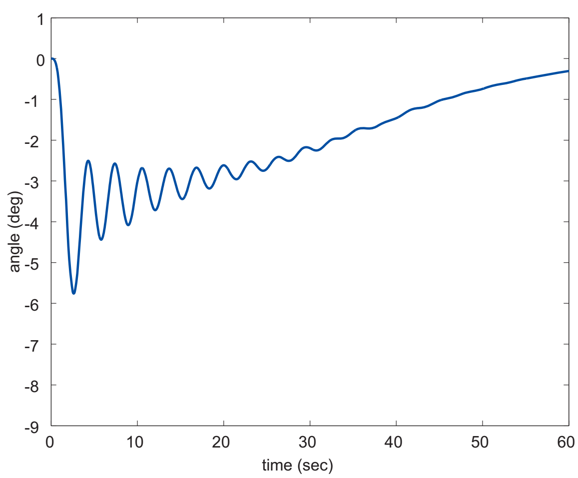

Fig. 32 Performance of the pilot model ($\omega_p = 2.0$, $\xi_p = 0.1$) : pitch angle

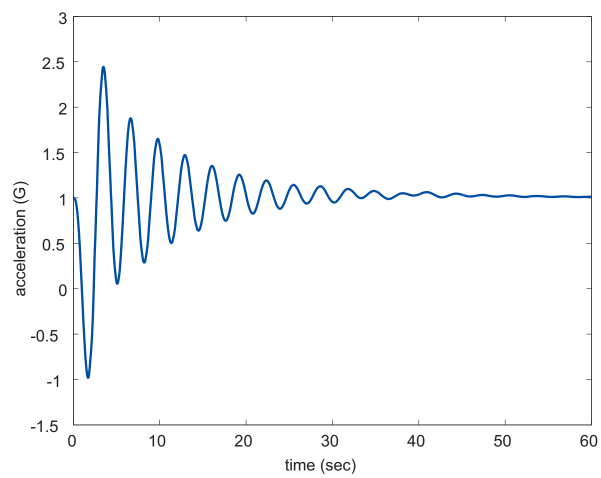

Fig. 33 Performance of the pilot model ($\omega_p = 2.0$, $\xi_p = 0.1$): vertical acceleration

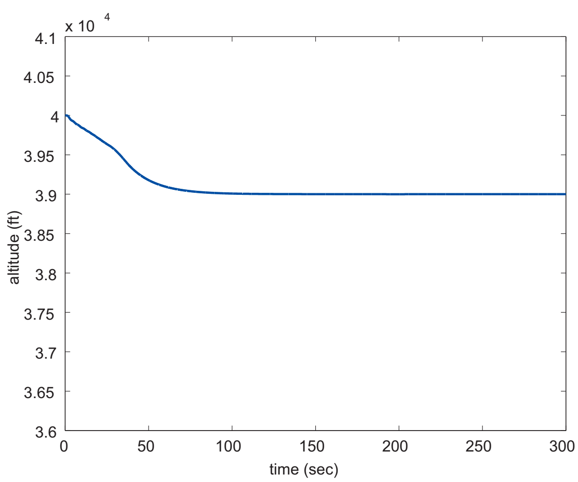

Fig. 34 Performance of the arbitrating system applied ($\omega_p = 2.0$, $\xi_p = 0.1$) : altitude

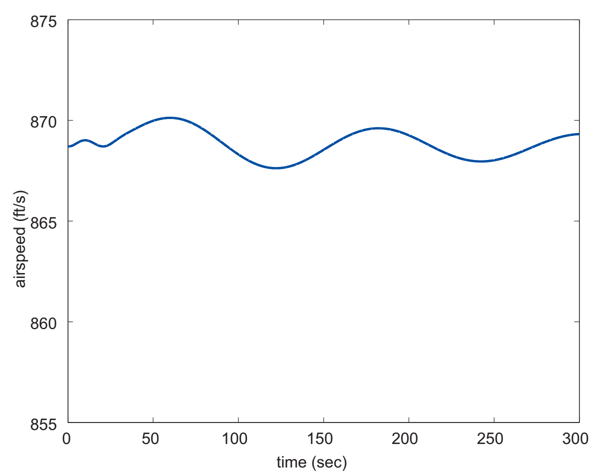

Fig. 35 Performance of the arbitrating system for the pilot model applied for the pilot model ($\omega_p = 2.0$, $\xi_p = 0.1$) :airspeed

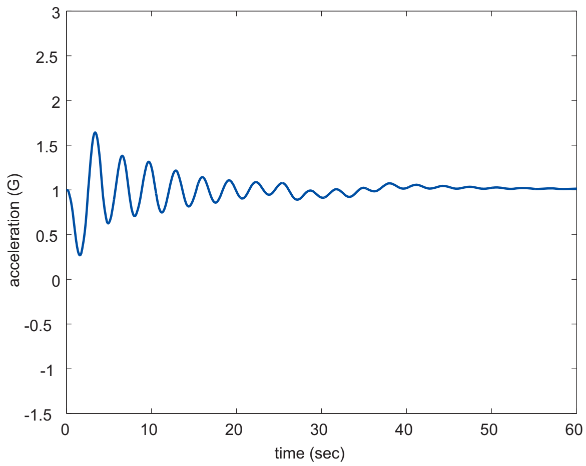

Fig. 36 Performance of the arbitrating system applied for the pilot model ($\omega_p = 2.0$, $\xi_p = 0.1$) : pitch angle

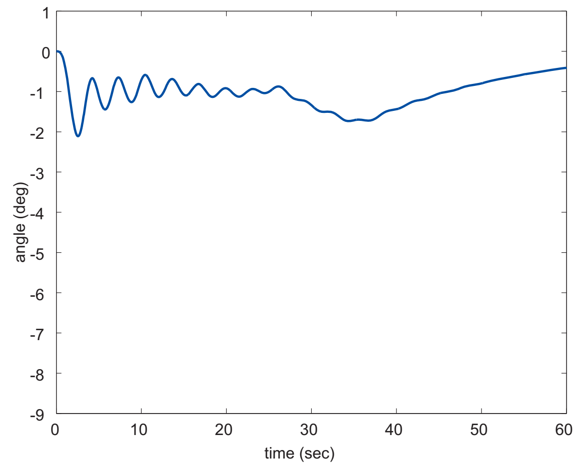

Fig. 37 Performance of the arbitrating system applied for the pilot model ($\omega_p = 2.0$, $\xi_p = 0.1$) :vertical acceleration

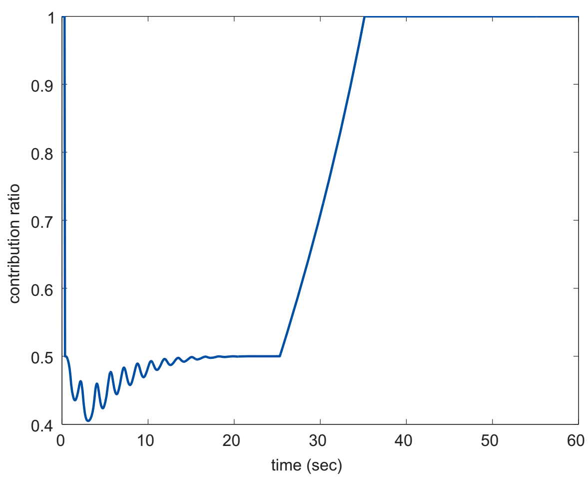

Fig. 38a Contribution ratio of ATCo

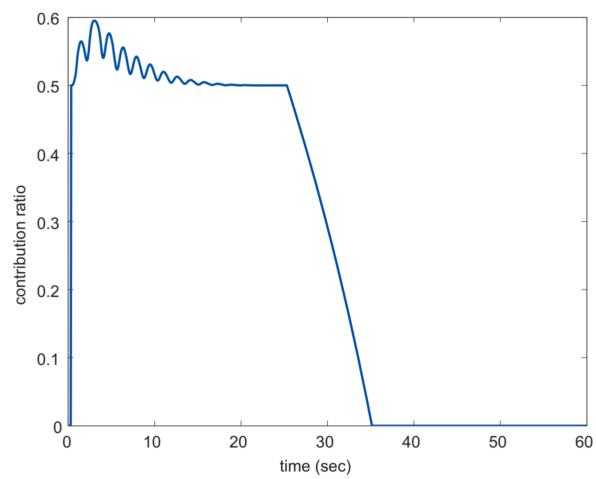

Fig. 38b Contribution ratio of AuATCo

utilize the arbitrating system online. Additionally, the simple architecture is effective for practical use because it will reduce the cost to confirm whether or not the new system works under any envisioned conditions. The arbitrating system is able to be introduced to the current flight control system, and it doesn't require the change of current autopilot design.

V. Conclusion

This research investigates the concept of the future air traffic management which introduces ground subliminal automation to the current air traffic management. In particular, the authors are interested in the analysis of the impacts caused by human-automation interaction from the control theory approach. The results of the analysis indicate that there exist interferences between air traffic controller (ATCo), pilot, and future ground automation (AuATCo) which disturb aircraft navigation parameters. These events occur when ATCo and AuATCo simultaneously work in the same control loop with different navigation strategy. In order to solve the problem, we discuss how control commands from ATCo and AuATCo in FMS shall be processed. This research proposes a new system called "arbitrating system" which automatically adjusts the control authority between ATCo and AuATCo during flight, depending on aircraft dynamics at the moment of decision. Obtained numerical simulation results confirmed that the arbitrating system solves all interferences, and contributes to safe aircraft navigation respecting ATCo instructions.

In current human-automation interface on board, it is indicated that there exists conflict between human (ATCo and pilot) and flight control system of the aircraft. Because it is difficult to understand how the flight control system is acting during the flight, pilots have confusion of how they should operate the automation system and control the aircraft following ATCo instruction. In the context of subliminal control system currently investigated in Europe, or similarly for future ground automation systems in NGATS, we need to keep it mind that both ATCo and AuATCo can simultaneously give different instructions to the aircraft, and can induce possibilities to disturb safety of aircraft navigation, by threatening the stability of the aircraft movement. In order to harmonize ATCo, pilot, and automation working together in the same control loop and to implement the future ground automation, it is necessary to introduce control authority "arbitrating system" for harmonizing human and automation.

The results obtained have been validated from three scenarios that are closest to the reality. It is a necessity to fully validate our approach by extending these scenarios to all possible ones. Also, in this paper, the arbitrating system is applied for one aircraft, and the authors are curious about the results of the application of this system to all aircraft in a sector. Moreover, final validation of the effectiveness of the arbitrating system also necessitates human-in-the-loop real time experimental simulations. For improving the accuracy of the predictor in the arbitrating system, we also need to observe the atmospheric disturbance and provide this information to the arbitrating system. The author applied the extended Kalman filter to observe the wind that aircraft intersects during the flight. For further consideration, it is necessary to discuss about how we observe and utilize the turbulence information in future Air Traffic Management automation.

APPENDIX

A. Aircraft Dynamics

1) Altitude

$$\dot{h} = -u \sin\theta + v \sin\phi\cos\theta + w \cos\phi\cos\theta + W_Z \quad \text{(A-1)}$$

2) Airspeed

$$\dot{u} = \frac{F_x}{m} - q\left(w + w_g\right) + r\left(v + v_g\right) - g\sin\theta - \dot{u}_g \quad \text{(A-2)}$$

$$\dot{w} = \frac{F_z}{m} - p\left(v + v_g\right) + q\left(u + u_g\right) + g\cos\theta\cos\phi - \dot{w}_g \quad \text{(A-3)}$$

F_x and F_z in Eqs. (A-2) and (A-3) are calculated as shown in following equations.

$$F_x = T - D\cos\alpha + L\sin\alpha \quad \text{(A-4)}$$

$$F_z = -D\sin\alpha - L\cos\alpha \quad \text{(A-5)}$$

Where

$$D = \frac{1}{2}\rho V^2 S C_D \quad \text{(A-6)}$$

$$L = \frac{1}{2}\rho V^2 S C_L \quad \text{(A-7)}$$

$$\alpha = \tan^{-1}\left(\frac{w}{u}\right) \cong \frac{w}{u} \quad \text{(A-8)}.$$

3) Pitch Angle and Pitch Angle Velocity

$$\dot{\theta} = q\cos\phi - r\sin\phi \quad \text{(A-9)}$$

$$\dot{q} = \frac{1}{I_y}\left\{\overline{M} + \left(I_z - I_x\right)pr + I_{xz}\left(r^2 - p^2\right)\right\} \quad \text{(A-10)}$$

Pitching moment $\overline{M}$ in (A-10) is shown as following equation.

$$\overline{M} = \frac{1}{2}\rho V^2 S\bar{c}C_m$$

$$= \frac{1}{2}\rho V^2 S\bar{c}\left\{C_{m0} + C_{m\alpha}\alpha + C_{m\dot{\alpha}}\bar{c}\frac{\dot{\alpha}}{2V} + C_{mq}\bar{c}\frac{q}{2V} + C_{m\delta e}\delta_e\right\} \quad \text{(A-11)}$$

Where

$$\dot{\alpha} = \frac{d}{dt}\tan^{-1}\left(\frac{w}{u}\right) = \frac{\dot{w}u - w\dot{u}}{u^2 + w^2} \quad \text{(A-12)}.$$

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C_D = drag coefficient

C_L = lift coefficient

C_m = moment coefficient

C_{m0} = airplane pitching-moment coefficient at zero α
C_{mq} = q derivatives describe the change that takes place in the moment m
$C_{m\alpha}$ = α derivatives describe the change that takes place in the moment
$C_{m\dot{\alpha}}$ = $\dot{\alpha}$ derivatives describe the change that takes place in the moment m
$C_{m\delta_e}$ = δ_e derivatives describe the change that takes place in the moment m
$\bar{c}$ = average aerodynamic cord
D = drag
E_{ij} = error index
F_x = external force following x direction of the body axis
F_z = external force following z direction of the body axis
g = gravity constant
h = altitude
h_c = command (target value) of altitude
I_x = inertia moment of x axis
I_y = inertia moment of y axis
I_z = inertia moment of z axis
I_{xz} = product of inertia $\int xz \; dm$
K = gain value
L = lift
$\overline{M}$ = pitching moment
m = mass of the aircraft
q = pitch angle velocity
r = yow angular acceleration
p = roll angular acceleration
S = wing area
s = Laplace operator
T = thrust
t = time
u = airspeed following x direction of the body axis
u_g = wind component following x direction of the body axis
u_k = input from the arbitrating system to the aircraft
V = airspeed
V_c = command (target value) of airspeed
V_ε = error value of flight path
v = airspeed following y direction of the body axis
v_g = wind component following y direction of the body axis
W_Z = wind component following z direction of the earth axis
w = airspeed following z direction of the body axis
w_g = wind component following z direction of the body axis
x_{ik} = input of a predictor
y_{ij} = output of a predictor
z_f = modification signal
α = angle of attack
ε_{ij} = error values between y_{ij} and target values
θ = pitch angle
δ_e = elevator angle
δ_{ec} = elevator command
δ_{Tc} = thrust command
ϕ = roll angle
ρ = air density
γ = flight path angle defined as $\dot{h}/V$
γ_c = command (target value) of flight path angle
γ_ε = error value of flight path angle
λ_i = contribution ratio

EUROCONTROL

A Note on the Flight-Level Assignment Problem

Alfred Bashllari, Dritan Nace, Jacques Carlier

Abstract— **This paper studies the flight-level assignment (FLA) problem. A better flight assignment can reduce the delay caused by airspace congestion. We first look at the complexity of the FLA problem and give a formal proof of its NP-completeness in the strong sense. We then focus on the probability conflict calculation problem and provide an approach taking into account the uncertainties based on Bayesian Network principles using Gibbs sampling.**

Index Terms—**Linear Programming, Conflict Probability, Bayesian Network, Gibbs Sampling.**

I. Introduction

Recent studies performed by EUROCONTROL Experimental Center (EEC) showed that a 5% to 6% increase in traffic results in about a 26% increase in delays, which suggests that alleviating delays caused by airspace congestion is, and will continue to be, critical to the operation of the European air traffic control system. Two kinds of congestion can be identified corresponding to two different areas of airspace: terminal congestion (around airports) and en-route congestion (between airports). In particular, in the European case, congestion is found predominantly in the airspace rather than at airports. Obviously there is not one global solution to this problem, but there are a lot of partial solutions that might enable the current Air Traffic Management (ATM) to meet all requirements. We are interested here in a specific direction involving flight-level optimization with respect to a given traffic demand and given routes. In other words, our goal is to reduce the total delay through a better assignment of flight levels, and this paper addresses the FLA problem (flight-level assignment). We restrict ourselves to only three possible levels for each flight. Despite this restriction, the problem remains highly combinatory due to the large number of simultaneous flights. An important question is how to include the en-route conflict probability in the model and take into account the uncertainties related to it. This may be done either through stochastic models, or through deterministic ones involving uncertainties in some way. We are mainly interested in this second type. Part of the work presented in the paper concerns an approach to the computation of en-route conflict probabilities based on a Bayesian network.

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The paper is organized as follows. In Section 2 we report the state of the art, related to works both in ATM and conflict probability estimation. In Section 3 we focus on the FLA problem. We show first the inherent difficulty of the FLA problem and provide an estimation method for the en-route conflict probability. Next, we present a 0/1 linear programming model. We conclude in Section 4.

II. Related Works

Optimization problems in ATM have been widely studied, and we do not intend to mention all of them. We prefer to focus exclusively on the flight-level assignment problem and the calculation of conflict probability. Let us first cite Bertsimas and Stock [2], [3] who have looked at the Air Traffic Flow Management Rerouting Problem (TFMRP), considering simultaneously the time and the route assignment problem through a deterministic approach. First in [2], they handle the Air Traffic Flow Management Problem (TFMP) with En-route Capacities, and then in [3] they show how to optimally control aircraft by rerouting, delaying, or adjusting the speeds of the aircraft in the ATC system to avoid airspace regions with reduced capacities due to weather conditions. Delahaye and Odoni in [6] study the problem of airspace congestion from the stochastic optimization point of view and propose a genetic algorithm. Barnier and Brisset (see [5]), consider the problem of level assignment while using an ideal sector-less environment. The main idea is to allocate different flight levels to intersecting routes in order to avoid conflicts. A straight line between an origin and destination pair represents the path of a flow of flights between these two airports; in other words, only direct routes are considered. Then, if two flows are in conflict, they must be routed on two different levels. The problem becomes a graph coloring problem: given a graph with a set of vertices and a set of edges, the problem is to color the edges such that any two intersecting edges (not at their extreme vertices) have two different colors, and the number of colors used is the lowest possible. Some other research on this problem, also based on the graph coloring problem is presented in Letrouit's thesis (see [12]). The route assignment problem here is handled by several tasks. The first task is minimizing the number of required levels when assigning each route to a level from the beginning to the end of a flight, and the second task is the distribution of routes among N levels in order to minimize the number of intersections between the routes having the same level. More recently, Constans et al. (see [16]) have studied the problem from the angle of aircraft speed modification. They propose minimizing conflict risks by dynamically imposing feasible modifications on the speeds of the aircraft. Doan et al. (see [4]) have presented a deterministic model intended to optimize route and flight-level assignment in a trajectory-based ATM environment. The aim of this study is to address the problem of airspace congestion, and in particular to reduce the number of potential en-route conflicts. This work was the starting point for the study presented here.

The second question considered in this paper is conflict probability estimation, which has been the subject of several studies. Let us first cite the work done by Erzberger and Paielli in [7], which describes the design of a conflict detection and resolution tool for use by en-route air traffic controllers. The design is based on an approach that combines deterministic trajectory prediction and stochastic conflict analysis to achieve reliable conflict detection. After the formulation of error models for the trajectory prediction, an efficient algorithm is described for estimating conflict probability. Empirical tests of the above method are reported in [8] by Paielli, where this procedure is tested with real air traffic data. Other work relating to Conflict Probability Estimation has been done by Irvine (see [9], [10]). Irvine describes a method for estimating conflict probability. Initially a method is presented which considers only along-track errors, but subsequently cross-track errors are included. In Irvine's paper only horizontal conflict probability is described, and it is assumed that the tracks are straight in the region where a conflict may occur. It is also assumed that the along-track error with respect to an aircraft's position is approximately constant and that the aircraft flies at its predicted speed. Given these assumptions it is concluded that the minimum displacement between two aircraft is a normally-distributed random variable. Bakker et al. have considered in [11] four conflict prediction approaches: the first is a classical geometric approach, the second the probabilistic approach described by Paielli and Erzberger, the third a variation of the second approach, and the fourth a novel probabilistic approach, based on collision risk theory. The novel probabilistic approach needs extra input parameters: the across-track and along-track standard deviation of velocity, and the size of the box which represents the aircraft.

III. The Flight-Level Assignment Problem

In this section we will study the FLA problem in more detail. We first establish the NP-hardness of the FLA problem in a general case. In III.A we present an approach for conflict probability estimation, followed by some numerical results. Recall that when dealing with the FLA problem, potential conflict probabilities are necessary input data. In III.B we provide a mathematical model associated with the FLA problem.

A. Complexity Issues

To the best of our knowledge, no specific work has been done on the theoretical complexity of the FLA problem. We will show that it is NP-hard in the strong sense, at least for a simplified version of the FLA problem. The problem is simplified to the extent that first we assume that flights do not necessarily follow straight lines, and secondly we do not consider conflicts involving more than a two aircraft. Although this simplified version does not entirely correspond to the FLA problem encountered in reality, we can reasonably assume that both of them are of the same difficulty. For the sake of simplicity, we will use the same name for both versions of the FLA problem. The proof is based on Graph (vertex) 3-Coloring (hereafter abbreviated to 3GC) known to be NP-Complete in the strong sense even for a planar graph. We will show below how 3GC can be reduced to the FLA decision problem, but let us first define these problems formally:

The decision 3-Graph coloring problem (3GC).
Instance: A planar graph **G = (V,E), a** set of 3 colors C and coloring function **c: V→C.**
Question: Is there any assignment of colors from C such that for any two adjacent vertices u, v we have **c(u) ≠ c(v)**?

The decision FLA problem.
Instance: A set of flights F, a set of preferred levels for each flight f, denoted L_f, and a function P: FxF→{0,1}, such that for each pair (f,f') of aircraft flying at the same level, P(f,f') = 0 if there is no en-route conflict between them and 1 if there is a potential conflict. Furthermore, we assume that en-route conflicts can occur only on the waypoints. Hence, two aircraft passing through the same waypoint within a short interval of time are assumed to be in potential conflict.
Question: Is there an assignment of flights to their preferred levels such that for any pair (f,f') of aircraft at the same level we have P(f,f') = 0?

Proposition 1. *The FLA problem is NP-complete in the strong sense.*

Proof. We will show that for any instance of the 3CG problem, we can construct in polynomial time an instance of the FLA decision problem that has a solution if and only if the 3CG has a solution. Let first show that the FLA decision problem is in NP: this is obvious, since we can verify in polynomial time whether or not for a given assignment of flights to levels there is any potential conflict. We simply need to check, for each pair of flights assigned at the same level, if there is some potential conflict, which gives at most n(n-1)/2 verifications (n = |F|).

Let us now consider the equivalence of these two decision problems. For any instance of 3CG we can construct an instance of FLA as follows:

Let G=(V,E) be a graph corresponding to an instance of the 3CG problem. Let us first define a one-to-onecorrespondence A between vertices in V and flights in the instance of FLA that we are constructing, that is |F| = |V|. Let us then use the vertices and edges in G to build an airspace network for the FLA instance. The network will be composed of 2|V| airports, |E| waypoints and only three levels (|L|=3). It can be shown that the corresponding graph is a planar one. With each flight f we associate a specific origin and destination airport, denoted respectively f_s and f_d. The waypoints are identified by a pair of flights corresponding to the extremities of vertices in G: for instance, a waypoint corresponding to edge e=(v,v')∈E will be denoted as (A(v),A(v'))=(f,f'). Then, for each flight f we associate a route from f_s to f_d passing through waypoints involving f (see Figure 1 for an example). It is straightforward that this construction can be done in polynomial time. We next show that solving the 3CG problem provides a valid assignment, i.e., avoiding conflicts, for the corresponding instance of FLA. Indeed, if we color the routes of some flight f in the airspace network with the color used for $A^{-1}(f)$ in G, we will never find two flights with the same color passing through the same waypoint, and hence no conflicts. Conversely, if there is a solution avoiding conflicts in our airspace network, let associate red with flights on the first level, green with those on the second, and blue with those on the third. By using this coloring for the corresponding vertices in G we obtain a solution for this instance of 3CG. As the 3CG problem is NP-complete in the strong sense, this proves that the FLA is as well, thus concluding the proof.

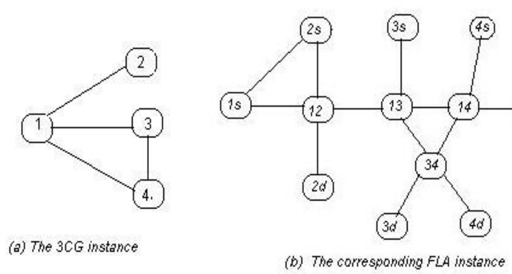

Fig. 1. FLA instance construction from 3CG.

B. *Estimation of conflict probability using Bayesian Network*

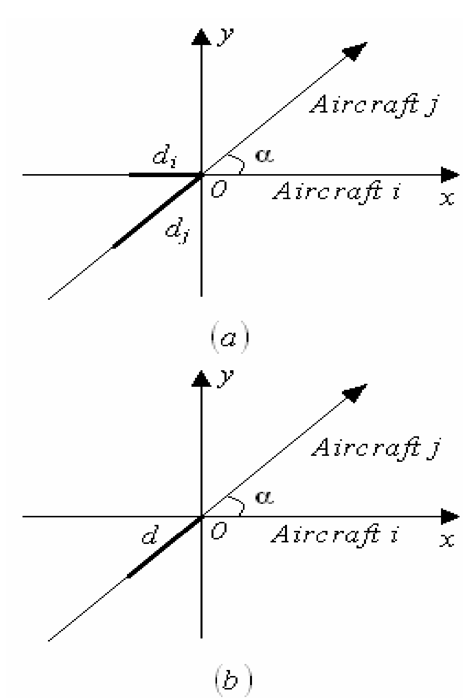

Fig.2. Conflict point between two aircraft in two-dimensional space.

In this paragraph we present a method for estimating the conflict probability between two aircraft by taking into account the uncertainties in their flight trajectories. Before presenting the conflict probability calculation approach, we should like to say a few words about how, given the flight plans; we estimate the risk of some conflict. To accomplish this we typically divide the time horizon into discrete periods of a few minutes. We recall that the trajectories of the flights and the take-off/landing times are already known.
This assumption permits us to compute the average aircraft speed and to predict approximately the time at which the aircraft will reach any point of intersection on its route. Hence, for two aircraft located in the same time period near the same point of intersection, we consider this point of intersection as a potential conflict point between them. Let us now recall how we calculate an essential parameter, which is the minimum distance separating two aircraft.

Notice that the "minimum distance" gives here the minimum separation between two aircraft, namely the real minimum distance between them but signed with + or − according to the sign of sin(α) (where α gives the angle between their trajectories). Let recall the "minimum distance" calculation problem as described in [13]. Without loss of generality, let us suppose that aircraft *i* precedes aircraft *j* at the conflict point *O* and that the trajectory of aircraft *i* is the *X* axis. At time $t_0 = 0$, aircraft *i* (respectively *j*) is at distance d_i (respectively d_j) from the origin *O* (see Figure 2(a)). At time $t^* = d_i / v_i$ when the aircraft *i* reaches the conflict point, the aircraft *j* has travelled a distance $d_j^* = (v_j d_i)/v_i$ where v_i, v_j are the speeds of aircraft *i* and *j* respectively. Hence, at time t_0 the distance *d* separating the aircraft *j* from the conflict point *O* (see Figure 2(b)) is given by:

$$d = d_j - d_j^* = d_j - (v_j d_j)/v_i \quad (1)$$

Let us now consider the distance between the two aircraft at some time *t*. Following the above, the position of aircraft *i* at time $t + t^*$ is $(v_i t, 0)$ and the position of aircraft *j* is $((v_j t - d)\cos(\alpha), (v_j t - d)\sin(\alpha))$. Consequently, the distance d_{ij} between them at time $t + t^*$ is such that:

$$d_{ij}^2(t) = (v_i^2 + v_j^2 - 2v_i v_j \cos(\alpha))t^2 + 2d(v_i \cos(\alpha) - v_j)t + d^2 \quad (2)$$

The function $d_{ij}^2(t)$ attains its minimum at time:

$$t_{\min} = -\frac{d(v_i \cos(\alpha) - v_j)}{v_i^2 + v_j^2 - 2v_i v_j \cos(\alpha)} \quad (3)$$

and the corresponding minimum value, noted $d_{\min}^2$, is such that:

$$d_{\min}^2 = \frac{d^2 v_i^2 \sin^2(\alpha)}{v_i^2 + v_j^2 - 2v_i v_j \cos(\alpha)}. \qquad (4)$$

Substituting (1) into (4) we obtain:

$$d_{\min}^2 = \frac{(d_j v_i - d_i v_j)^2 \sin^2(\alpha)}{v_i^2 + v_j^2 - 2v_i v_j \cos(\alpha)}. \qquad (5)$$

We can rewrite (5) as follows:

$$d_{\min} = \lambda(d_j - \rho d_i) \qquad (6)$$

where $\lambda = \dfrac{\sin(\alpha)}{\sqrt{\rho^2 - 2\rho\cos(\alpha) + 1}}$ and $\rho = \dfrac{v_j}{v_i}$.

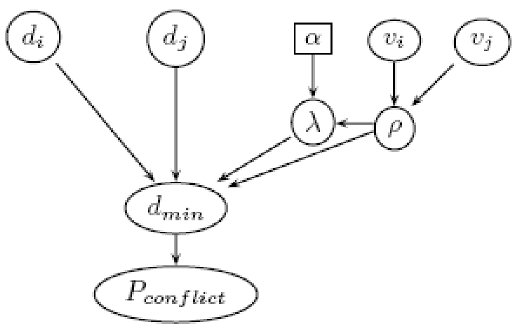

Fig. 3. Bayesian Network for conflict probability estimation.

So, we calculate the "minimum distance" between two aircraft as a function of the aircraft speeds, of the distances of the two aircraft from the conflict point at some time, as well as of the angle between aircraft trajectories.

We now introduce a Bayesian approach based on the formula of "minimum distance" between two aircraft as given in (6). We include different sources of variations, such as delay at the origin airport, weather conditions, uncertainty in the aircrafts' velocity, reduced visibility etc.. All these additional sources of variations are integrated into the model, assuming that the speeds of the aircraft and the distances of the aircraft from the conflict point are random variables with normal distributions. Under these hypotheses we estimate the conflict probability using Bayesian simulations.

Description of the Bayesian Network

We show in Figure 3 how a Bayesian network can be built from the formula of "minimum distance" given in (6). Recall that a Bayesian network consists of a network structure that encodes a set of conditional independencies between different variables, and a set of probability distributions associated with each variable. The structure of the Bayesian network is a directed acyclic graph [14]. We begin by determining the variables to model. The chosen variables for the calculation of conflict probability are the distances d_i and d_j of aircraft from conflict points, the speeds v_i, v_j of aircraft, λ and ρ. The angle between the aircraft trajectories is considered constant and is given as input data. Of course, more variables could have been included. To construct the Bayesian network for our set of variables, we simply draw arcs from cause variables to their immediate effects. The structure of the Bayesian network and the states of variables are shown in Figure 3.

In the next step of constructing the Bayesian network we report the probability distributions associated with each variable. We assume normal distributions for the d_i and d_j variables, with mean equal to the distance of aircraft from the conflict point at the start of the corresponding period. Also, we assume normal distributions for the v_i, v_j variables, with mean equal to the average speed of aircraft during the corresponding period. Concerning the standard deviation values for the distanceand speed distributions, we distinguish three different cases (see Figure 4). Once the Bayesian network has been built, we need to determine the probability of conflict, given observations of the other variables. This probability depends on the difference between the required separation (*s = 5 nmi*) and "minimum distance". We have:

$$P_{conflict} = step(s - abs(d_{\min})), \qquad (7)$$

where:

$$step(e) = \begin{cases} 1 & e \geq 0 \\ 0 & e < 0 \end{cases}. \qquad (8)$$

Finally, we recall that the parameters involved in the model are assumed to follow some known prior distributions. Their values are generated by the WinBUGS program using Gibbs sampling.

Numerical results

All the tests were run on a machine with the following configuration: Windows XP, 1 Pentium 4 2.4GHz processor, 1 GB of RAM. The test data correspond to French air traffic on August 12th 1999 with 1697 flights, 134 airports and 769 used waypoints. The granularity of time used in our tests is 10 minutes. To calculate the probability of conflict with the Bayesian approach, we create a model using the BUGS language and then run it in WinBUGS1.4 [15]. In Figure 4 we report the conflict probability values for three different cases for a sample of 60 predicted conflict points.

Bayesian 1: Standard deviation for d_i, d_j equal to *0.1* and for v_i, v_j equal to *1.0*.

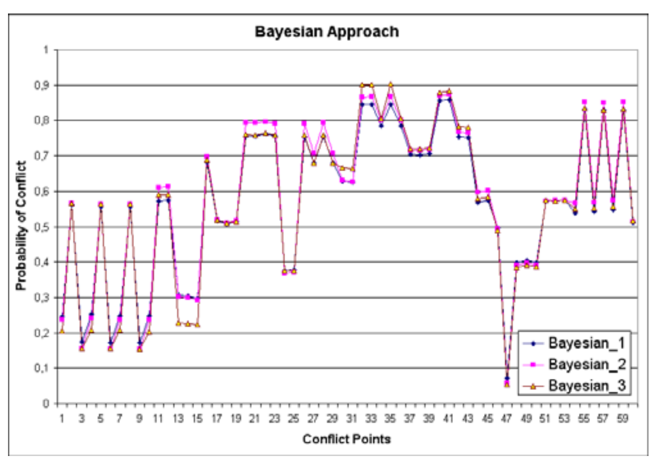

Fig. 4. Conflict's probability estimations for different cases of Bayesian approach.

Bayesian 2: Standard deviation for d_i, d_j equal to *0.1* and for v_i, v_j equal to *1.2*.
Bayesian 3: Standard deviation for d_i, d_j equal to *0.3* and for v_i, v_j equal to *1.0*.

As illustrated in Figure 4, the difference between the values of probability of conflict calculated with the Bayesian approach for the three above cases is quite small. This means that the standard deviation of distances from the conflict point and the speeds of the two aircraft have little impact on the probability of conflict.

C. A mixed integer linear programming model

Let us now return to our initial problem. We provide below an MIP (Mixed Binary Linear Programming) model of the FLA problem.

In this work, we have taken into account the potential conflicts and the corresponding probability as computed above. We consider only the level assignment problem, assuming that the routes through the waypoints in the network are already fixed. We are restricted to the case of fixed single routes and we do not consider the possibility of route change. In our view this remains relevant, since it is the flight-level optimization that ensures the greatest improvement in congestion reduction *(see for instance [4]).*

Notation

- L denotes the set of possible flight-levels l.
- F denotes the set of flights.
- $x_{i,l}$: binary variable (0,1), takes the value 1 when the flight i, flies on level l and 0 otherwise.
- $p_{i,j}$: gives an estimation of the delay associated with aircraft i when resolving a potential conflict with aircraft j. Note that usually we have $p_{i,j} \neq p_{j,i}$. They are constant data already estimated in our problem thanks to the probability of conflict computed above, distance to the conflict point, speeds etc..
- P_i*: gives* the total delay for a given flight i.
- S_i *:* gives the set of flights j having a potential conflict with flight i.
- $l_{i,j}$: binary variable (0,1), takes the value 1 when the flight i and j fly on the same level and 0 otherwise.

In reality, the set of flight-levels L depends on the type of aircraft, and therefore on the flight. For the sake of simplicity we have assumed that this set is the same for all flights. In reality, the set of admissible flight-levels associated with a flight typically depends on the type of aircraft.

Mathematical formulation

This problem can be mathematically stated as below:

$$\text{Minimize} \sum_{i \in F} P_i$$

Subject to:

$$\forall i \in F \qquad \sum_{l \in L} x_{i,l} = 1 \tag{9}$$

$$\forall i, j \in F, l \in L \qquad x_{i,l} + x_{j,l} \le l_{i,j} + 1 \tag{10}$$

$$\forall i \in F \qquad \sum_{j \in Si} p_{i,j} l_{i,j} \le P_i \tag{11}$$

$$\forall i \in F, l \in L \qquad x_{i,l} \in \{0,1\} \tag{12}$$

$$\forall i, j \in F \qquad l_{i,j} \ge 0 . \tag{13}$$

The objective function tends to minimize the total delay in the airspace. The set of constraints (9) enforces a unique level for each flight. The set of constraints (10) ensures that the variables $l_{i,j}$ are binary. The set of constraints (11) measures the total delay associated with aircraft i. The remaining two constraint sets (12) and (13) specify that the $l_{i,j}$ variables are nonnegative integers, and that the $x_{i,l}$ variables are binary. Notice that the flight-level assignment problem is addressed here as a mixed-integer linear programming problem with binary variables, which in practice will be difficult to solve to optimality. Notice also that the model can be further enhanced, for instance by imposing a maximum delay for each flight or by including an additional term in the objective function to reflect the penalty of assigning a flight to a less appropriated/preferred level.

IV. Concluding Remarks

We study in this paper the FLA problem. We have shown that the problem is NP-complete in the strong sense and have provided a simple method for estimating the conflict probability based on the Bayesian approach. The obtained probabilities are frequently used as input in mathematical models. We propose a 0/1 linear programming model for the FLA problem. At this stage, we are interested in studying the structure of the obtained matrix and associated polyhedral aspects. This work is ongoing.

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Migration of Analogue Radio to a Cellular System - Sector Change without Frequency Change

Horst Hering, Konrad Hofbauer

***Abstract* - The capacity of the current ATC system is among other factors limited by a maximum number of aircraft that can be handled by a controller in a sector. This led in the past to a decrease of sector sizes in order to increase capacity. We study in this paper the impact of small sectors on the air/ground radio communication. Small sectors require a large number of radio channels, and the sector handovers generate multiple radio calls, which are workload for both controllers and pilots. We outline in this context an initial idea to make the control sectors transparent for the aircrew. With a grid of radio base stations and reduced transmission powers a cell-based end-to-end communication system can potentially be established, without changing from analogue to digital radio. The aircraft transmits on the same frequency across all sectors, and the voice calls are routed by the ground infrastructure to the appropriate controllers. We discuss potential benefits and issues of this concept and see a clear need for further research to determine the feasibility of this idea.**

***Index Terms* – sector-less radio communication, operational concept, channel frequency change, workload,**

I. Introduction

SINCE its beginnings, Air Traffic Control (ATC) has relied on the voice radio for communication between aircraft pilots and air traffic control operators. The amplitude-modulation (AM) radio, which is in operation worldwide, has basically remained unchanged for decades. Given the aeronautical life cycle constraints, it is expected that the analogue radio will remain in use for ATC voice communication in Europe well beyond 2020 [1]. The AM radio is based on the double-sideband amplitude modulation (DSB-AM) of a sinusoidal carrier. For the continental air-ground communication, the carrier frequency is within a range from 118MHz to 137 MHz, the 'very high frequency' (VHF) band, with a channel spacing of 8.33 kHz or 25 kHz.

This avionic radio is the main tool of the controller for giving flight instructions and clearances to the pilot, where several people use the same radio channel. This is usually called a "party-line", used on a time-shared base by one air traffic controller and all aircraft in the corresponding flight sector. In order to establish meaningful communication, all pilots start their messages with the verbal call-sign to identify themselves to the controller. Vice-versa, the controller starts the message with the call-sign of the aircraft. Call-sign mishearing, misunderstanding and call-sign confusion are an important issue in ATC safety. A recent EUROCONTROL study [2] showed: "Incidents involving air-ground communication problems between controller and pilots are rare and encompass about 1% of all reported incidents and 23% of ATC related incidents". Reducing the risk of wrong identification and thereby increasing the level of safety in ATC is the motivation for research in this area.

EUROCONTROL predicts a shortage of VHF frequencies within the current VHF communication system for 2015 [12]. A project called 'B-VHF' [7], supported by the 6th framework programme of the European Commission, proposed an interim broadband solution overlaying the current communication concept. The proposed concept requires major changes in the onboard and ground equipment.

However, as the shortages of the current communication concept are quite different for the major international players North America and Europe, there is on time no international high-level agreement for such a solution. Nevertheless, it is expected that the next generation communication standard will move from analogue party-line communication towards a digital end-to-end communication. The digital concept favours direct data exchange between onboard and ground systems. For security reasons however the human voice communication will always persist.

This paper presents innovative concept ideas, which potentially allows the current analogue party-line voice communication to move towards an end-to-end oriented communication concept. It prevents frequency shortage and supports new operational concepts with digital communication features at an earlier time than it is foreseen for the digital communication concept to be implemented.

II. Digital Features for the Analogue Radio—State of the Art

By using so-called 'speech watermarking' techniques, it is possible to embed digital information, such as aircraft call-sign, unique aircraft identification address or tail number, into the analogue voice communication. It is thus possible to transmit in conjunction with the voice transmission the identification of the aircraft. The transmitting aircraft can then be unambiguously identified by the ATC ground system by extracting the embedded aircraft identification. An embedded watermark is unnoticeable for humans in the received speech communication. In 2003 such an embedding of a digital signature as watermark in the pilot's voice was proposed as Aircraft Identification Tag (AIT) [3, 4]. An 'AIT – Initial Feasibility Study' [8] was launched by the EUROCONTROL headquarter in 2006. The study reported no potential technical constraints for a realisation [9].

In extension to the air to ground downlink of the aircraft identification, the destination address of a ground to air uplink voice message could be included in the controller's voice communication. Therefore the current controller working procedure for calling an aircraft would have to be changed, as the controller has to indicate the destination address of the aircraft to which he/she attends to speak. A study showed that such a change could be acceptable by the controllers [5].

Embedding AIT data in the down- and uplink radio communication promise safety benefits for controller

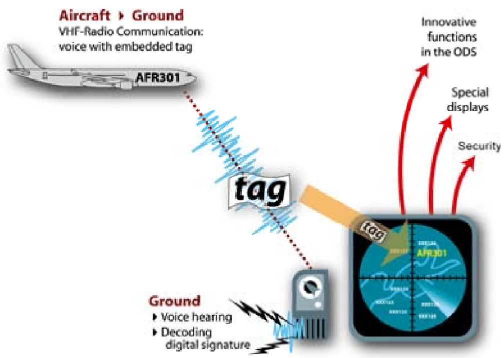

Fig 1. AIT – Aircraft Identification Tag

andaircrews and it allows securing the legacy radio communication by the exchange of encrypted signatures, as proposed by the European Community project SAFEE [6].

A study on new AIT embedding algorithms [10] reports data embedding rates up to 2000 bit/sec, which is higher than the rate of 100 to 150 bit/sec required in the 'AIT - Initial Feasibility Study' [8].

The legacy analogue radio communication system is known for its poor quality. Embedding digital data in an analogue voice signal additionally opens perspectives for further applications like channel equalisation, bandwidth extension or de-noising. The digital features could enhance the voice quality. Better radio intelligibility and automatic identification and authentication would bring benefits for ATC's safety and security.

III. Impact of Sector Size on Radio Communication

Air ground voice communication plays an essential role for the safety of flights in controlled airspace. In today's two-man cockpits it is usually the 'pilot non-flying' who communicates with the ATC station. This pilot has to monitor all communications on the voice channel attentively in order to filter out controller messages addressed to his flight. In core Europe with small and highly charged sectors, pilots have to change the sector communication frequency in the course of a flight very frequently. The communication task may interfere with other onboard tasks.

Controller's mental capacity is limited for example by the number of aircraft handled at a time, and therewith limiting the sector capacity. It was common practice in the past to educe the size of the sectors. This increases the number of sectors in a given area and therewith the control capacity of this area. Today, the limit to reduce the sector size is reached in many areas. For example, in core Europe many sectors have a fly through time as low as five to eight minutes. Small sectors and frequent sector changes interfere with the currently used control concept in terms of communications in three different aspects:

Number of available radio channels

- Generation of speech acts on the radio channel
- Potential loss of communication

A. *Number of Available Radio Channels*

Each sector requires an associated sector frequency (channel). For safety reasons, the reuse of the same frequency is possible in very distant sectors only (~1000nm). Worldwide about 760 channels are available for the civil ATC communication in the VHF (Very High Frequency, 118MHz…137MHz) band. Internationally a channel spacing of 25kHz is used. For some areas in Europe a channel spacing of 8.33kHz is established in order to overcome the channel shortage. Nevertheless EUROCONTROL predicts a channel shortage for Europe by 2015 [12].

B. *Generation of Speech Acts on the Radio Channel*

Due to the current ATM concept the radio channels are highly charged with pilots and controller speech acts. VOCALIS [11] studied 60 hours of voice communication in twelve distinct French en-route sectors featuring heavy traffic periods. On average VOCALIS report 324 air-ground speech acts per hour, which are more than 5 controller/pilot utterances per minute.

A major part of the air ground voice communication is generated by the need to transfer and assume the control of an aircraft from one sector to the consecutive one. Each transfer and assume consists of two speech acts: a request and its acknowledgement. VOCALIS [11] reports: "Voice exchanges taking place during transfer or assume phases account for the majority of controller-pilot communications (about one out of two speech acts is at least partly related to either transfer or assume in VOCALISE samples)."

Over 50% of the speech acts issued on the radio communication channel are related to the sector change. Figure 2 shows a flight plan sample of a flight from Toulouse to Hamburg in July 2005. The overall flight time was 124 minutes, thereof 88 minutes was cruising in en-route sectors above FL245. During its cruising time the flight crossed eight en-route sectors. In this example, the flight across the 'Sollingen' sector (second last sector before the destination) lasted about eight minutes. The 'Sollingen' sector capacity is around 50 aircraft per hour. Consequently, the pilots and the controller will issue on the sector frequency 200-speech acts per hour (more then three per minute) in relation with sector changes. The sector changes generate a significant workload for pilots and controllers.

Controller Pilot Data Link Communication (CPDLC) allows to uplink the transfer information for the pilot to contact the next sector [14]. The silent assume of an aircraft at the next sector is for safety reasons not foreseen to be implemented. Therefore pilot has to inform the controller of the next sector of his presence by a call on the radio channel. With a larger deployment of CPDLC the congestion of the voice communication channel will be reduced.

Fig 2. Flight Toulouse – Hamburg

C. Potential Loss of Communication

Sector changes are a potential source for an interruption of the radio communication with the assuming control sector. For the transfer of an aircraft to the consecutive sector a controller will transmit a voice message on the sector frequency similar to: "Lufthansa tree four niner contact Bremen radar on frequency one two six decimal six five". Several factors, such as human's imperfection in speaking and understanding, low transmission quality, or pilot errors, might lead to the frequency not being changed or the wrong frequency being selected. In such a case the aircraft enters a sector without radio contact to the responsible controller. This creates at least supplementary workload for the pilot and the sector controller and may cause a hazardous situation. A EUROCONTROL study [2] reports as highest contribution factors in 'loss of air ground communication' occurrences radio interference with 29% and the frequency change with 25%.

IV. Issues of the Future Air Transportation

Global civil air transportation can be seen as two major groups:

- General aviation and
- Commercial airliners.

A. Future general aviation traffic

Currently the airspace usage of the two groups is quite different. Rohacs [16] report that the crowded flight levels used are separated by more than 20000 feet. Figure 3 shows the flight levels used by commercial airliners and general aviation for the European airspace (source: Rohacs [16]). Predictions for the traffic growth of small aircraft are even higher than for the airliner. In example, Cessna currently delivers globally about 1200 aircraft [17] a year. Thereof a third is equipped with jet engines (~300 jets and ~100 turboprop). Rolls–Royce [18] forecasts for the next two decades the delivery of over 30000 business jets. These jets will use similar flight levels as commercial aircraft today. Therewith the flight level usage of the small aircraft will move strongly towards flight levels currently used by of the commercial airliners. Pilots of small aircraft will be to great

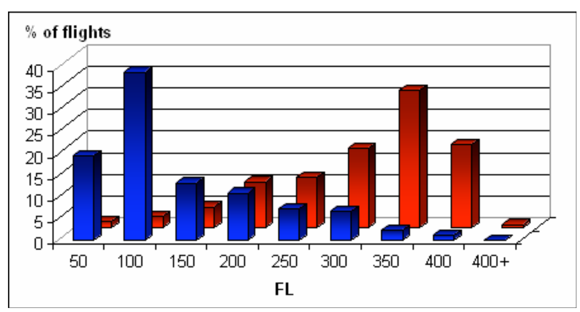

Fig 3. Flight level distribution for commercial (red) and small (blue) aircraft flights (source: Rohacs [16])

majority private pilots. Private pilots usually have less experience and training as their commercial colleagues. Moreover, many small aircraft have one pilot, only. This issue is addressed by the NASA SATS (Small Aircraft Transportation System) [19] project started in 2005.

B. The future cockpit of commercial airlines

In 1920 KLM (Royal Dutch Airlines) started as a pioneer the commercial passenger transportation. During the first decades aircraft seat capacity was limited. In the early fifties of the last century the number of passengers was growing and bigger aircraft were required. Lockheed's Super Constellation reached the mark of one hundred passengers. The flight crew of the Super Constellation cockpit consisted of 5 peoples: pilot, co-pilot, navigator, radio operator and engineer. Today cockpits consist in general of two pilots: pilot flying and pilot non-flying. Figure 4 shows the reduction of the flight crewmembers during the past fifty years by some examples. Currently further reduction of flight crew to one pilot is in discussions.

In 2004 the DLR (German Aerospace Centre) conducted an experimental flight of an Unmanned Aerial Vehicle (UAV) through controlled German airspace. The pilots 'flying and non-flying' were located at a ground station. They operated the complete flight and ground manoeuvring via data link. For security reasons a backup flight crew was seated in the experimental aircraft, a Fokker VFW614.

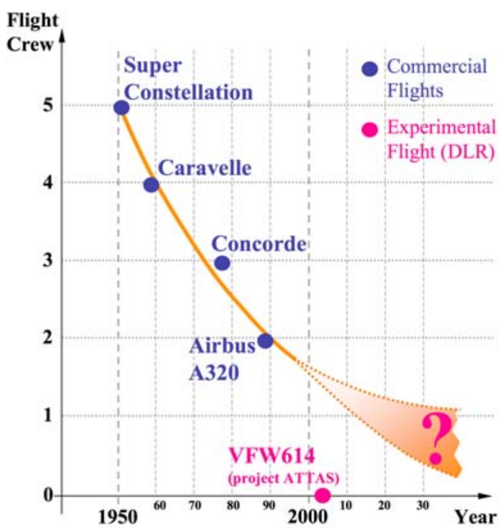

Fig 4. Flight crewmembers in commercial aircraft

V. END-TO-END RADIO COMMUNICATION

Chapters 'III. Impact of sector size on radio communication' showed the mainly technical impact of the current ATM concept (reducing sector sizes to increase capacity) on the radio communication. The previous chapter 'IV. Issues of the future air transportation' gave a perspective of future air transportation under the aspect of an increasing number of less trained and experimented pilots in probable single pilot cockpit. Today, one of the main tasks of a second pilot (pilot non-flying) is the ATC radio communication. A single pilot cockpit will require a radical review of the current radio communication concept.

Digital end-to-end communication is a good candidate for a required new radio communication concept. End-to-end radio communication makes the ATC sectors transparent for pilots, it avoids frequency changes for pilots and therewith it eliminates the risk of lost radio communication. First steps towards an end-to-end communication are made with the deployment of ATC data link communication but on time (end of 2007) there is no global decision on a future digital the radio communication concept.

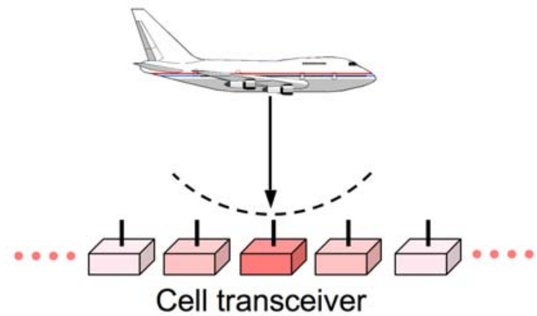

Fig 5. Communicating with a single cell transceiver

The following section describes new ideas how end-to-end radio communication could be emulated by the current on-board radios. The idea is subject of further research initiated by the EUROCONTROL Experimental Centre.

A. Broadcast radio communication with party-line feature

Today's ATC radio communication broadcasts the speech over a wide area. This creates automatically a so-called party-line effect. Currently the party-line effect is seen as positive aspect for pilots' situation awareness. The authors of this paper put in question the importance of this positive party-line effect with regard to following facts:

- It's internationally agreed that by time data link communication shall replace voice radio communication (except for emergencies). Data link communication is an end-to-end communication, which gives no so-called party-line information to pilots.
- ICAO (International Civil Aviation Organisation) has four official languages (English, French, Spanish, Russian), which might be spoken on the international ATC radio communication channels. So in example a pilot of a foreign aircraft crossing upper French airspace communicates in English with the French ATCO. In the same time French aircraft in the sector might communicate in French with the ATCO on the common radio channel. In such a case an increase of pilot's situation awareness related to hear party-line communication, is limited to the knowledge of the presence of other aircraft in the sector.

B. New Technical Concept for the ATC Radio Communication

The EEC initiated an initial feasibility study of the emulation of end-to-end radio communication with the current analogue radio communication standard. The proposed new end-to-end concept is based on the mobile telephone (GSM - Global

System for Mobile communications) principle that communicates by low transmission power with the nearest ‘cell’ of the fixed telephone cell network.
Transferring this principle to the ATC radio communication would imply a significant reduction of the aircraft transmission power, as the nearest ‘cell’, straight below the aircraft, of a new ground infrastructure (ATC communication network) has to be reached, only.
Following two assumptions are made for the concept:

- All aircraft voice messages have an embedded digital signature (i.e. call-sign) using AIT techniques (see chapter ‘II. Digital features for the analogue radio’),
- The controllers have to indicate to the communication system the destination address (call-sign) of the aircraft at the start of the radio call. (EEC study [15] with twelve operational experts showed a large acceptance for such a change of the current working procedures.)

The proposed technical concept interconnects aircraft transceivers and the nearest cell transceiver of a new ground infrastructure using low power radio transmissions. The cells of the ground network are connected to a cell transceiver management unit. This allows the current party-line based communication concept to move towards an end-to-end communication concept similar to advanced digital communication of the ATC future.

C. Potential benefits and issues of end-to-end communication

The benefits of an end-to-end like radio communication are:

- Avoids shortage of communication channels
- Eliminates radio channel speech load caused by sector changes
- Reduces controller workload related to sector change voice messages
- Eliminates sector change task for aircrew
- Eliminates aircrews party-line monitoring task
- Eliminates the risk of loosing communication by errors related to frequency changes.

Detailed Human Factor (HF) studies shall be launched to identify the potential workload benefits for aircrews and controllers. These HF studies may quantify how far the expected workload reductions influence the overall control capacity.
End-to-end radio communication will enable new operational concepts. With end-to-end communication sectors become an ATC internal issue, as they are invisible for the aircrew. Collapsing or separating sectors due to operational requirements will be managed by reallocation of the network cells in the cell transceiver management unit to different controller working positions.
Figure 6 shows a possible sectorisation of the represented area with three sectors. In the example the green sector controller currently controls the aircraft. Soon the aircraft will reach a cell that is associated with the blue sector. From that time on the aircraft communicates by its position with the blue cell, and this communication is linked on ground to the blue controller. As all cells use the same radio channel (frequency) the sector change is completely transparent for the aircrew. Ground coordination between controller blue and green is however required.

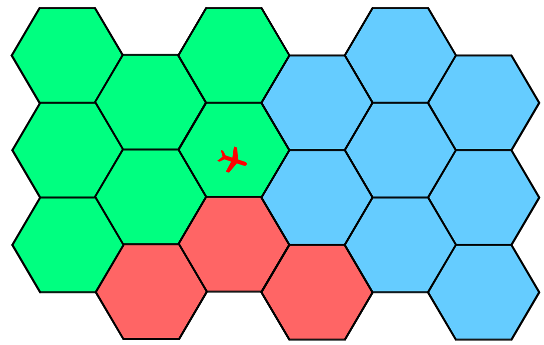

Fig 6. Sectorisation with a cell structure

Today, the operational concept reached nearly its capacity barrier. This ATC capacity barrier depends on several constraints. Some of the constraints may be circumscribed by technical means, but the human mental capacity of the controller is a constant value. Hence reducing the sector size cannot be seen as a solution for the future especially as it creates supplementary workload for the cockpit and the risk to loose radio communication. End-to-end radio communication could play a major role to increase the overall ATC capacity of the current ATC concept. in this way the next generation communication concept will be end-to-end.
Our current route structure is highly optimised to avoid build-in structural conflicts as far as possible. One-way traffic on a route is widely used for this purpose. A project partly financed by the European commission deals with the aspect of Super Highways for the airspace. In such a concept a highway consists of two independent carriageways, one for each direction. Each carriageway in its complete length would represent an independent longish ATC sector. End-to-end radio communication would be the ideal radio communication concept for the carriageways. Hence a carriageway sector could be split in as many parts (cells) as required by ATC issues. As the carriageway sector with all its cells use a unique communication channel (frequency) the aircrew would see one continue ATC sector only.

Figure 7 shows another solution for the control of the highway. Therewith a controller stays responsible for one or more aircraft for the time of their highway flight. The Figure 7 shows five aircraft communicating with the cells below which are linked by the cell transceiver management unit to the responsible controller of the green, orange and blue cells. With flight progress aircraft’s cell connection will change but the cell transceiver management unit will link the new cell to the same responsible controller.
The size of the cell for the end-to-end radio communication

determinates how far new operational concepts may go. A logical limit might be: *one aircraft – one cell*, consequently end-to-end radio communication could support new operational concepts up to the extreme: *one controller – one aircraft.*

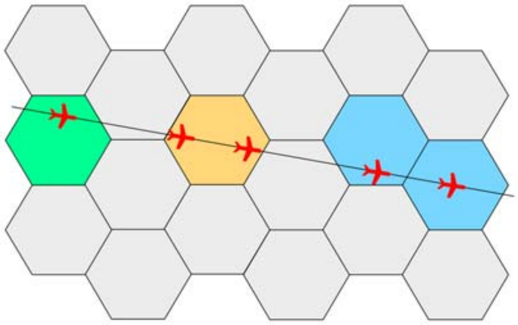

Fig 7. SuperHighway with end-to-end radio communication

The concept includes the AIT concept and therewith its benefits for safety and security.

Following concept issues are identified and have to be studied:

- Controller agreements for flexible aircraft handovers are not supported.
- The sector wide party-line is reduce to a party-line with cell size.
- As no sector wide party-line exists, simultaneous calls of multiple aircraft have to be handled on a technology level.

VI. Conclusion

It is internationally agreed that a change towards digital radio communication is required. The digital communication would most likely implement an end-to-end radio communication concept. Due to different constraints based on continental issues a digital standard and a time scale for its implementation is not yet defined.

The proposed concept in combination with AIT brings digital features to the legacy analogue radio communication and allows an operation similar to a digital end-to-end manner. It represents an intermediate step towards the radio of tomorrow using technical standards of yesterday.

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Quantification and Forecasting of Emissions from Taxiing Aircraft

Benjamin Levy, Kevin Lefebvre, and Jeff Legge

***Abstract*— The European Commission proposes to cap emissions from civil aviation at levels averaged over the 2004-2006 period. The legislation intends to reduce rapidly-growing greenhouse gas emissions contributed by civil aviation from its current 3% portion of total emissions of EU countries. The legislation applies to most air traffic between the EU countries by 2012 and permits the buying and selling of emissions allowances.**

Implementation of this emissions reduction program requires the ability to quantitatively measure and forecast emissions at airports. Data exist with which to measure and forecast emission; these data are provided by existing, advanced airport surface surveillance systems. These data can be analyzed and integrated with calculated excess taxi times to quantify the emissions from taxiing aircraft. Sensis Corporation is a major provider of surface surveillance systems (A-SMGCS, MLAT), and has developed procedures and algorithms to automatically calculate excess taxi times, process the data and quantify emissions on a *per* aircraft basis. The emissions estimates for taxiing aircraft may be separated into a minimum (achievable) emissions level and an excess (reducible) emissions level.

This work presents details and results on emissions quantification from taxiing aircraft as a day-of-operations capability or as a control (i.e., reporting) mechanism based on historical data. This work also shows that it is possible to accurately forecast excess emissions from taxi data using time-series techniques such that planning in advance (e.g., months ahead) may be performed.

***Index Terms*—Fuel Burn Rate, Aircraft, Taxi Times, Emissions**

I. INTRODUCTION

THE impact of aviation on the environment has not slipped passed the airline industry, the standard bodies, and various governmental agencies. For instance, one of Single European Sky ATM Research's (SESAR) Key Performance Areas is Environmental Sustainability, where environmental sustainability is defined as achieving environmental, economic, and social balance within the constraints of airport demand. The overall goal of SESAR is to have a 10% reduction in aviation's impact on the environment, taking into account the flight demands, local and global environmental constraints and airport operations. The International Civil Aviation Organization (ICAO) has also taken a position to limit or reduce the impact of emissions on local communities as well as the global community. The policies of the U.S. Next Generation (NextGen) plan include addressing the environmental impact of aviation on local and global communities. Adhering to all these requirements defined by these groups will be challenging, given the fact that worldwide demand for air transportation is increasing.

The environmental effects referred to above are divided into two categories: noise and emissions. Emissions, which is the focus of this paper, is mainly due to CO, CO_2, NO_x, and H_2O where CO, CO_2, and H_20 are related to the amount of fuel burned and the amount of NO_x produced is related to the combustion chamber of the engine. Reduction in CO, CO_2, and NO_x can be achieved through improvements in engine technology, but with the increasing demand for air travel, reducing emissions through engine technology will be offset by an increase in the number of flights. Furthermore, an increase in the number of flights can increase in the delay time for each flight further offsetting the effects in improvements of engine technology. This implies that improvements in engine technology *and* improvements in operations are required.

Increasing efficiency or improving operations stems from the fact that delays within the lifecycle of the flight can be large. For instance, 60% of the delay time in the U.S. occurs during departures resulting from the increase in demand. The U.S. is not alone; within Europe, delays have increased 9.5% from 2005 to 2006 while demand has also increased. The overall result of increasing demand is increased delays, fuel usage and emissions, which decreases the chances of meeting the requirements of SESAR, ICAO, and NextGen.

Improving the operation performance to control the emissions requires understanding the amount of excess fuel burned during each stage of the flight's lifecycle when delays are present. This requires understanding the amount of additional time the aircraft is running during taxi-in/taxi-out, queuing, approach, landing roll, takeoff roll, and climb out and integrating this with the amount of engine usage and fuel burn rate to each flight phase. Once this information is known, an evaluation on where to focus operational efficiencies can be achieved. One portion of the lifecycle of

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the flight, excess taxi times, will be the focus of this work. The total taxi time can be separated into an excess taxi time and a minimum, unimpeded taxi time. The excess taxi time is due to unnecessary holding, which leads to excess fuel burn, emissions, and cost. The minimum, unimpeded taxi time is the quantity to which a well-operated airport should strive to achieve and maintain. For demonstration purposes, the excess amount of taxi-time for Detroit Metropolitan Wayne County (DTW) Airport will be calculated along with the excess amount of fuel burn and resulting emissions generated. The calculations are based upon data generated from Sensis Corporation's surface multilateration system at DTW, algorithms developed at Sensis relating to Surface Management, and ICAO's engine data. ICAO engine data are used to calculate the amount of fuel used per aircraft engine along with the amount of CO, NOx, and HC generated.

This work presents an example of the use of surface surveillance data to quantify excess taxi time during airport operations. Two examples of the quantification of fuel burn and emissions are presented. The first will be an analysis of historical data; this can be performed either as a real-time, day-of-operations function or as a retrospective assessment. The second shows how the schedule of departures can be used to forecast the average excess taxi time over the duration of a future month, such that that the excess fuel burn and emissions can be estimated.

II. Post-Event Fuel Burn Analysis

A. *Historical data and methodology*

The estimation of fuel consumption and emissions from taxiing aircraft is based on the analysis of surface surveillance data. The surveillance data provided by the multilateration system at DTW Airport is accurate and frequent (i.e., nominal one sec frequency) position data for each aircraft as it taxis on the airport surface. Provided that the transponder is switched on, the taxi times from push-back to wheels-off for a departure and wheels-on to gate for arrivals are measurable. The wheels-off time and wheels-on time are defined by the time at which the ground speed passes through 70 kts. The criterion of 70 kts is chosen to be conservative such that the wheels-off time for slower aircraft is measured; realistically, commercial aircraft leave the ground at faster ground speeds (e.g., 120 kts), so the wheels-off time for a departing commercial aircraft is underestimated, perhaps by no more than 20 seconds at 150 kts lift-off ground speed. For arrivals, the wheels-on time at 70 kt ground speed overestimates the wheels-down time by a similar magnitude for faster-landing commercial aircraft.

For an arrival, the transponder is on from wheels-on to gate, allowing estimation of the gate-in event time from the multilateration position. For departures, however, the push-back time cannot be reliably measured from the multilateration data because the transponder is often not turned on until the pilot receives the clearance from the ground controller to enter the taxiway. In the United States, the ramp and gate are controlled by the airline ramp controller, who clears the pilot to push-back. Upon reaching the jurisdictional boundary between ramp and ground control (commonly referred to as the "spot"), the pilot halts the aircraft to await clearance from the ground controller; it is typically while waiting, at least at DTW Airport, that the transponder is switched on, making the position of the aircraft available to the multilateration system.

A surface diagram for DTW Airport is show in Figure 1, translating surface surveillance data into taxi paths. On Figure 1, the map polygons that subsume the locations of the gates and ramps are shown as magenta-bordered regions (i.e., "ramp" polygons). The "ramp" polygon for the three taxiing

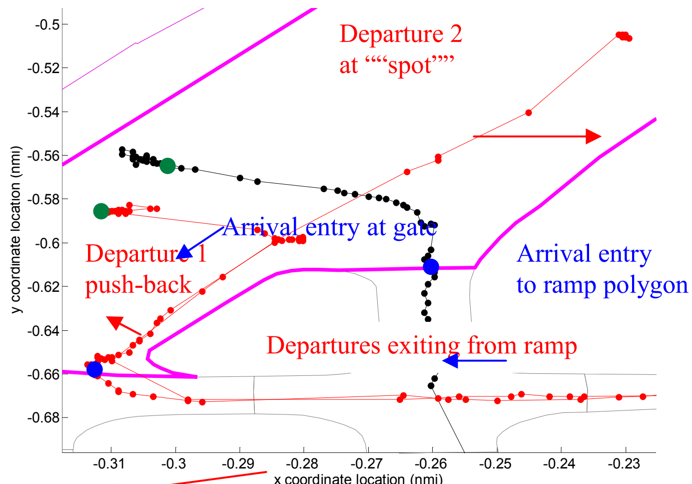

Fig. 1. Definitions of In and Out Events

aircraft is shown with a heavy magenta-colored line. Map polygons defining the movement area (taxi-ways, runways) are shown as gray-bordered regions. The three taxi-path trajectories are described by two departures (red traces) and one arrival (black trace); the positional data are shown by small, colored dots.

Referring again to Figure 1, the location of aircraft at the moment of entry and exit from the ramp polygon are shown with large, blue-colored dots; the two departures exit from the ramp polygon at nearly the same location. The locations of the gate-in and push-back events (if known) are shown in large, green-colored dots. As can be seen, there is a push-back event for "Departure 1", but not for "Departure 2" because the transponder for the latter departure was not switched on until it reached the "spot". Because many of the departures do not have measurable push-back time, the taxi-out time is defined as the time at which the aircraft leaves its originating map polygon and enters the taxiways and is directed by the ground controller. The "in" event time is similarly defined as the time at which the aircraft enters the map polygon containing its destination gate. The taxi time durations are minimums and do not include the time spent at the gate or at the "spot."

It is a truism that unnecessary delays during taxiing produce excess fuel consumption and emissions. It is, however, only with high-quality surface surveillance data that the total taxi-time may be separated into a minimum, unimpeded taxi-time and an excess taxi-time. In this work, we aver that holding of taxiing aircraft due to congestion (i.e., queues) and policy (i.e., first-come-first-serve clearance delivery) defines the excess taxi-time to be minimized by automation or collaborative decision making. Under this assumption, we will measure the excess taxi-time as the time spent by a taxiing aircraft as it holds in the taxi-way network. For this, we have developed an algorithm to measure holds in the taxiing position data, provided that the duration of the hold is at least five sec. For the nominal one-second frequency positional update rate, this means that a hold is defined by at least five positional reports in near proximity. Use of this algorithm allows quantification of the magnitude and location of holding that generates the excess taxi-times. This is demonstrated in Figure 2, where holds experienced by taxiing aircraft are shown January 31, 2007 during de-icing operations at DTW Airport. Figure 2 illustrates holding of

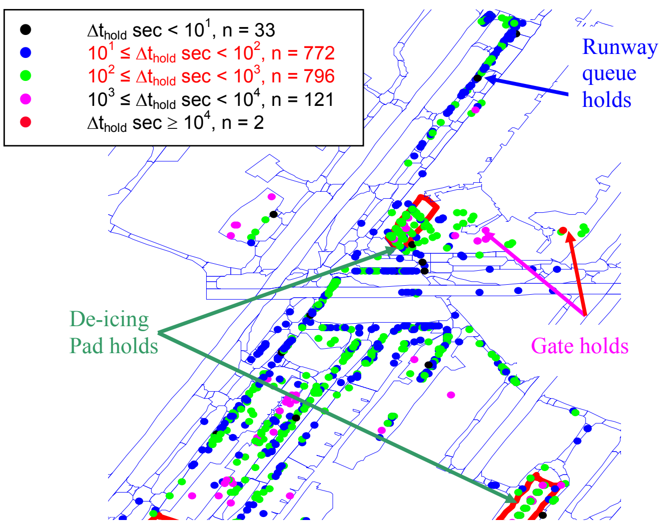

Fig. 2. Holding in Taxiing Departures Under Deicing Operations on January 31, 2007 at DTW Airport.

departures waiting to enter the deicing pad (red-bordered polygons) on part of DTW Airport. Holds are colored-coded by order of magnitude of duration (sec).

Figure 2 shows that the most frequently occurring hold durations are between 102 and 103 seconds (n = 796 holds), as depicted by the green-colored dots. Many of these holds occur at the holding pads and in queues leading to the hold pads. Longer holds (e.g., greater than 103 sec) are denoted by magenta or red-colored dots and are usually at the gate.

The estimation of the fuel consumption and emissions requires the integration of the excess taxi time with the aircraft type. The multilateration system reports the mode S code and the tail number, which can be correlated to the aircraft type with the US FAA aircraft registry. This applies to US-domestic registered aircraft. For an identifiable aircraft type, the fuel burn rate and emissions rates were obtained from the ICAO engine database [2] for aircraft idle mode. Table 1 provides a summary of the most-commonly occurring aircraft types at DTW Airport, based on two dates (May 24, 2006 and January 31, 2007). For the 10 most common aircraft types, the fuel burn rate is reported in varying units (e.g., kg/sec/eng); the emissions rates as lb-emissions per 103 lb fuel burned are also given for hydrocarbon (HC), carbon monoxide (CO), and nitrous oxides (NOx) pollutants.

As shown in Table 1, the surveillance data had 1612 aircraft with identifiable types that were present in the ICAO database. Of these, the top 10 most common aircraft total to 1405 (87% of the 1612 quantity). Also in Table 1 is the total number of aircraft for which the type was unknown (i.e., n = 1413) and the number of aircraft with a known type but not present in the ICAO database (i.e., n = 106). Table 1 also presents weighted averages for fuel burn and emissions rates for the top-ten most-common aircraft and for all aircraft with known fuel burn and emissions rates. It can be seen, with the exception of the weighted averages for HC emissions (i.e., 5.51 lb/103 lb for top-10 vs. 7.04 lb/103 lb for all aircraft with known rate data), that the weighted averages of fuel burn rate

TABLE 1
AIRCRAFT TYPE FREQUENCY, FUEL BURN RATE, AND EMISSIONS RATES FOR DTW AIRPORT

		fuel burn rate	emissions rates ($lb/10^3$ lb)		
aircraft type	count	(gal/min/eng)	HC	CO	NO_x
CL-600	353	0.94	8.69	93.72	8.40
DC-9	266	2.78	2.75	23.10	7.04
A319	174	1.91	3.08	38.72	8.80
A320	134	1.91	3.08	38.72	8.80
SAAB340B	124	0.28	8.80	77.88	4.84
B737	107	2.15	5.02	75.68	8.58
B757	97	3.59	2.20	33.97	9.46
EMB-145	58	2.44	8.36	31.46	6.93
AVRO146-RJ85A	56	0.77	11.86	90.05	8.32
B717	36	1.89	0.24	43.38	8.69
"top-10" (type/rate known)	1405	1.80	5.51	57.39	7.95
type known/rate known	1612	1.82	7.04	62.57	7.93
unknown type	1413				
type known/rate unknown	106				

and emissions rates for the top-10 category and the known-rate category are very similar. This suggests that the weighted fuel burn and emissions rates can be used to reproduce emissions for the cases where the aircraft type or rate data are unavailable.

In summary, the key assumptions behind calculation of the fuel-burn and emissions are:

1. Taxi-times are minimal because measurements do not include holding in the ramp area
2. The fuel burn/emissions characteristics for aircraft with unknown type are described by the weighted average of aircraft of known type and fuel burn/emissions rates
3. The total taxi time is separable into an unimpeded and an excess taxi times, where the excess taxi time

is identified by holds (i.e., zero ground speed) of at least five sec duration

4. Fuel burn and emissions are calculable from the total, excess, and unimpeded taxi-time and the aircraft characteristics, assuming that only one engine is used during taxiing
5. Computation of expenses on fuel is based on 4.70 USD per gallon Jet-A fuel

B. *Economic Analysis*

Based on the assumptions and analysis described in the preceding subsection, the results from the analysis of two dates of operations at DTW Airport are presented and shown in Table 2 where date one (May 24, 2006) represents a day of fair-weather operations and date two (January 31, 2007) represents a day during which de-icing operations were conducted. Table 2 shows the taxi-time estimates for arrivals and departures on both dates. For example, on May 24, 2006, there were 616 arrivals and 593 departures. Table 2 also shows the total, minimum (unimpeded), and excess taxi-times are reported in columns identified with brackets [1], [2], and [3], respectively. For example, the total taxi-in time on May 24, 2006 was 5,200 minutes. Also presented in Table 2 are the totals for fuel consumed and fuel cost based upon the taxi times, the aircraft type (Table 1), and assumptions above. The total, minimum, and excess taxi-in times are approximately the same for arrivals on both dates, suggesting that the operations at DTW Airport are independent with respective to arrivals and departures. Also, the taxi-in times are generally less than the taxi-out times, as expected, because of spacing discipline enforced on arrivals before landing. Finally, on January 31, 2007, the de-icing operations almost doubled the excess taxi-out time over the fair-weather operations on May 24, 2006

The results in Table 2 can be put in perspective with annualization based on operations counts for DTW Airport. Taking the total operations counts for 2006 from the US FAA ASPM database, we scale the results in Table 2 by assuming that two weeks of the year are represented by the delays during de-icing operations of January 31, 2006. Table 3 presents the results of the annualization and scaling of data in Table 2. The result of the scaling estimates that the total fuel expenditures were 49.3 M USD. Of this quantity, 10.6 M USD (2.2 M gal) is identifiable as excess fuel expenditure and consumption.

III. SCHEDULE-BASED FUEL BURN ANALYSIS

The second application of surveillance data and aircraft type data is in the estimation of the time-varying excess average taxi-out time at DTW Airport. Given the schedule for departures, it is possible to estimate the excess average taxi-out time with dynamic linear regression. A Matlab toolbox, CAPTAIN, from Lancaster University was used for time-series model identification, calibration, and validation [3].

It is assumed that the minimum taxi-out time is dictated by the distance traveled between gate and runway. This implies an assumption that the excess taxi-out time is independent of path and is controlled by congestion. The independent variable is the number of scheduled departures per 10-minute interval; the dependent variable is the average excess taxi-out time for the same 10-minute interval (see Figure 3). The average taxi-out times were calculated assuming that there were three or more departures per time interval and that the maximum average taxi-out time is 120 minutes (exceeded 13 times of 12,151 observations in May 2006).

The time-series model was calibrated using the excess taxi-out times and scheduled departures for April 2006 at DTW Airport, with an $r^2 = 0.73$. Taking the model coefficients from the calibration, the model was used to predict the average excess taxi-out time using the scheduled departures for May 2006 ($r^2 = 0.68$) and January 2007 ($r^2 = 0.63$). The smaller r^2 value for January 2007 reflects the occurrence of irregular operations (e.g., de-icing) not present in the calibration data set for April 2006. Regardless, the quality of the correlation for the calibration and validation is sufficient to allow prediction of the average excess taxi-out time with scheduled data as a forecasted process (e.g., month in advance). Note that at an airport without time-variable departure rates, the relation between average excess taxi-out time and number of scheduled departures may be poor.

The product of the number of scheduled departures and the average excess taxi-out time per departure can be integrated for the time period of April 2006 (15,322 departures), such that the total average excess observed taxi-out time for April 2006 is 9.0×10^5 min; the total average excess predicted taxi-

TABLE 2.
TAXI TIME, FUEL BURN, EXPENDITURE, AND EMISSIONS ESTIMATES FOR TWO DIFFERENT OPERATIONAL CONDITIONS AT DTW AIRPORT.

				taxi-time ($\times 10^3$ min)			fuel consumed ($\times 10^3$ gal)			fuel cost ($\times 10^3$ USD)		
date	condition	ads	ops	[1]	[2]	[3]	[1]	[2]	[3]	[1]	[2]	[3]
1	fair wx	arr	616	5.2	4.0	1.2	8.6	7.1	1.5	40.4	33.4	7.0
		dep	593	7.8	5.8	2.0	14.4	10.9	3.5	67.8	51.4	16.4
2	de-icing	arr	599	5.8	5.0	0.8	10.5	9.3	1.2	49.4	43.7	5.7
		dep	625	18.2	10.2	8.0	36.8	16.8	20.0	173.2	78.8	94.4

TABLE 3
ANNUALIZED TAXI-TIME, FUEL CONSUMPTION, AND EXPENDITURE FOR DTW

	no. of	Taxi-Time (min)		Fuel Consumed (gal)		Fuel Cost (USD)	
ads	operations	Total	Excess	Total	Excess	Total	Excess
arrivals	242,000	2.1 M	0.5 M	3.5 M	0.6 M	16.4 M	2.7 M
departures	244,000	3.7 M	1.1 M	7.0 M	2.2 M	32.9 M	10.6 M
total	486,000	5.8 M	1.6 M	10.5 M	2.8 M	49.3 M	13.3 M

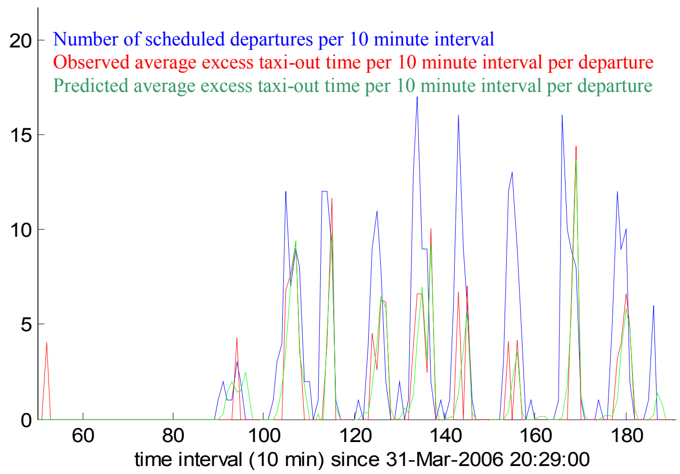

Fig. 3. First Day of Calibration of Time Series Data, April 2006

out time for April 2006 is close, at 8.3 x 10^5 min. Note that these numbers are close to the 1.1 M number reported in Table 3 for excess taxi-out time. Using the assumptions on fuel cost and weighted averages for fuel burn and emissions, the annualized excess quantities from pro-rating the integration of the April 2006 data are 1.639 x 10^6 gal consumed, 7.7 x 10^6 USD spent on fuel, and emissions of HC (8.1 x 10^4 lb), CO (7.2 x 10^5 lb), and NO_x (9.1 x 10^4 lb). Note that even if the April 2006 data are pro-rated to an annual basis by assuming that two weeks of the year experience twice the taxi-out times due to de-icing operations, the total excess taxi-out times from the time series approach is less than the aircraft-specific historical analysis. This may be because the distribution of taxi-times is skewed-right such that the average is an underestimate of the process.

IV. CONCLUDING REMARKS

In this work, the minimum, excess, and total taxi times were calculated for DTW Airport. Surface surveillance data was obtained from Sensis Corporation's surface multilateration system. Taxi times were estimated and integrated with the ICAO engine database to calculate the excess emissions and fuel usage. It is observed that excess taxi times substantially increase the fuel usage and emissions. It was demonstrated that time series analysis tools can accurately predict the excess taxi times, fuel usage, and emissions. Therefore, by using surface surveillance data along with analysis tools, predictions can be made on a per-aircraft basis of how much fuel will be used and how the fuel usage translates into emissions generated. This will allow the airlines and airports to better plan for reducing their environmental effects.

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EUROCONTROL

An Air Traffic System Paradigm for Direct Routing and Low Conflict Rates: some Feasibility Issues

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***Abstract*—The present ATM system will not cope with the forecasted growth of air traffic. In this paper we envisage an alternative paradigm for the operation of air traffic, characterized by a high degree of organization. Aircraft are compelled to precisely follow immaterial moving points regularly generated on the direct route joining their origin to their destination. In this paper we address the problem of determining which among the moving points can be allowed and which of them should be forbidden in order to obtain a very low conflict rate. First elements about the existence of a solution are presented.**

***Index Terms*— Air Traffic, ATC, ATM, Conflicts, Graph Theory**

I. Introduction

Two main objections can be made today to the present ATM system.

Firstly, traffic monitoring and conflicts solving are based on a division of the airspace into control sectors, each of which having a capacity in terms of number of aircraft allowed to enter it during a time period. In the context of a quasi-continuous growth of air traffic movements, one of the most used methods to increase the overall capacity of the air traffic system has been until now the dividing of overcrowded control sectors into smaller ones. It is easy to understand that this possibility will not last forever. Indeed a small sector is more difficult to monitor than a large one and traffic growth is forecasted by Eurocontrol Performance Commission to be at a 3% rate each year up to 2012 [1].

Secondly, the system is based on the use of a trunk route network which imposes an average route lengthening of 5.9% compared to the use of orthodromic or "great circle" routes [1]. The consequences are in 2006 an additional distance flown of 441 millions kilometres, with estimated costs to airspace users of 2 230 millions of euros. Moreover, route extension has a direct impact on the environment, as additional CO_2 emissions reach 4.7 millions of tons, which is not acceptable in the context of a growing awareness of the world public opinion on climate change. So it is necessary to envisage the use of an orthodromic routes network that allows direct routing between origin and destination. The present use of a trunk route network is consistent with an air traffic monitoring based on a division of airspace into control sectors, because it concentrates an important part of the conflict risks on the nodes of the network, making the conflicts monitoring and solving job easier for air traffic controllers (ATCOs). The use of an orthodromic network will generate a huge number of intersections, far more important than in a trunk network, that will have to be monitored by ATCOs, leading to an important increase of their workload.

For all these reasons, in the long term, it is necessary to envisage an alternative paradigm for the ATM system. The operation of autonomous aircraft ensuring themselves their own safety has already been proposed and studied by the ATM community and seems promising. What we propose here is to study another approach, in the opposite direction, where the air traffic or a part of it, is completely organized. In this approach, aircraft fly on orthodromic routes and are sequenced in a way that results in a very low average conflict rate. It makes it possible to use a monitoring and solving process not based on the division of airspace into a large number of sectors.

The paradigm is as follows: on each orthodromic route defined by an origin, a destination and a given cruise flight level, fictive and immaterial moving points are generated at a regular pace. There are two types of points, some of them are *forbidden*, the others *allowed*. Aircraft are compelled to precisely follow allowed points. The problem is then to determine for each flight level a subset of the Origin/Destinations (OD) that are assigned to it and for each of these ODs an assignment of the status forbidden or allowed, so that there is no conflict between aircraft following allowed points or, if not possible, very few. In this paper, we address some feasibility issues concerning the problem of the assignment of allowed moving points to the ODs.

II. Related Work

Recent studies try to propose systems with reduced conflicts rate.

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A first approach consists in modifying existing airspace structure. In [2], the authors build a regular lattice covering the European core area. Aircraft have to follow these tracks. This structure consists in a couple of (opposite) directions for each of 9 consecutive flight levels. When climbing from a flight level to the next one, the direction of the tracks increases by 45° clockwise. It means that aircraft have to change of flight level if they want to turn. In order to let aircraft turn, spacing of tracks has to be large enough, so the authors decided to take a 70 NM distance between each track for even flight levels (FL 300, FL320,..., FL380), and a 50 NM distance for odd flight levels (FL 310, FL330, ..., FL370). In [3], the author proposes to create two freeways (from Ireland to Turkey, and from Baltic Sea to Spain) at high altitude, and at different flight levels. For each direction, these freeways consist in two or more parallel lines, horizontally separated. Specific rules apply for these freeways, mainly to join and leave them. The aim is to absorb intercontinental traffic and a part of long European traffic.

Despite their promising results, these approaches generate additional travel distance, since aircraft are not allowed to fly directly from their origin to their destination. Other approaches, including ours, consider orthodromic routes and try to avoid potential conflicts. For instance, in [4], the authors propose to vertically separate intersecting aircraft flows by assigning different flight levels. They reduce to classical graph theory problems, such as maximal clique and χ-colouring [5]. In[6], the authors propose a network in which routes are a set of successive segments on the same direction (the orthodromy) but at different flight levels, in order to avoid potential conflict points.

Another way to avoid conflicts is short-term speed control. In [5], the method consists in minimizing potential conflict quantity in a sliding horizon loop process by slightly modifying aircraft speed. In [8], the author recommends a subliminal control approach to resolve conflict. It can be done by slightly modifying the (horizontal and/or vertical) aircraft speeds, so that controllers do not see the difference and that conflicts are avoided. This is the framework of the ERASMUS project.

III. Presentation of the Paradigm

A. Concepts

The Air Traffic system that we study is based on two concepts:

- Aircraft fly on a direct route from their origin to their destination. We call *axis* such a route in this document.
- On each axis, there are moving points (represented by circles in Fig. 1) that move regularly in the same direction so that two consecutive moving points are separated by the same time period (that we call moving points period per axis). Two types of moving points exist: *allowed* and *forbidden*. Aircraft are forced to precisely follow allowed moving points during their cruise, and are not allowed to stand outside these allowed moving points. From an operational point of view, a new type of automatic pilot would take care of precisely following moving points. Cruising and descending phases are not included at the moment in our model, and will be envisaged later.

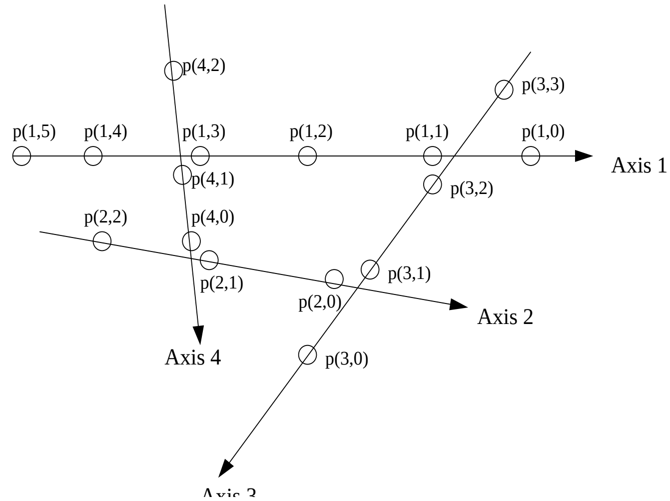

Fig. 1. Axis graph (Moving points are denoted by p(i,j) where i stands for the axis and j for j^{th} moving point on the axis)

Our problem is to assign to each moving point a status, either allowed or forbidden, such that there are no conflicts (or at most very few) between any two allowed moving points. For instance, in Fig. 1, moving points p(1,3) and p(4,1) are in conflict and thus cannot both have the allowed status. Recall that one can (potentially) allocate one aircraft per allowed moving point with the guarantee that no conflict occurs at any time.

The quality of such an allowed/forbidden assignment can be evaluated in many ways:

- We can focus on the occupation rate, defined on an axis as the number of allowed moving points over the total number of moving points on that axis. The mean occupation rate is the mean of all occupation rates per axis. We can try to maximize the mean occupation rate in order to maximize the network flow capacity. However this criterion is not really appropriate as it can lead to non-realistic solutions. For instance, if we maximize the mean occupation rate in Fig. 1, the optimal solution consists in setting all the moving points of axes 1 and 2 as allowed, and all those of axes 3 and 4 as forbidden (or vice-versa): thus no aircraft can fly along these latter routes. Instead, one can think to maximize the lowest occupation rate of the axes, but the same drawback occurs. Indeed an optimal solution may contain an arbitrarily long sequence of consecutive forbidden moving points. To avoid these cases, we introduce a new objective function.
- We call a solution $\frac{1}{k}$-dense if and only if there are at most *(k-1)* successive forbidden moving points on any

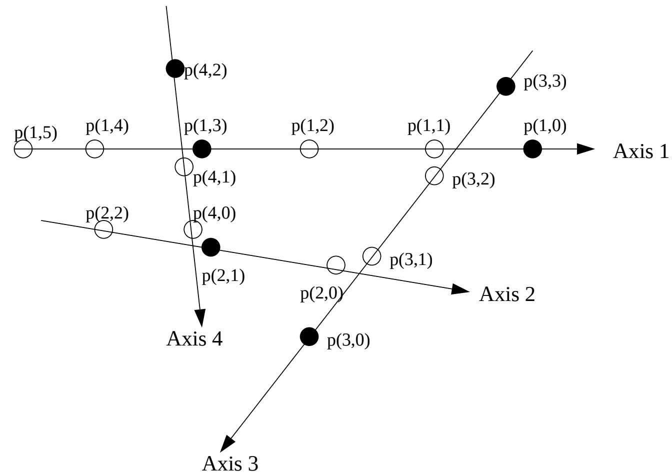

Fig. 2. 1/3-dense solution for axis graph defined in Fig. 1

axis. It means that, if we take k successive moving points, at least one is allowed. From an operational point of view, it implies that an aircraft will not have to wait on ground for more than *(k-1)* moving points before an allowed moving point can be reached at its cruise level. For instance, the configuration in Fig. 1 has a $1/3$-dense solution, exposed in Fig. 2 (where allowed moving points are represented by dark-filled circles, and forbidden ones by white-filled circles).

We decide to take the $\frac{1}{k}$-density as objective function for the moving point assignment problem in order to get operational solutions.

B. Hypotheses

In its current form, our model is based on two hypotheses:

- A moving point from axis i cannot be in conflict with more than one moving point from axis j. Hence it is necessary to define a sufficient distance between moving points, depending on the angle of intersections we want to deal with and on the separation standards, assumed here to be 5NM. For instance, a 10 NM distance is sufficient to satisfy this hypothesis for angles up to 120°. 15 NM are needed for angles up to 140°.
- We introduce a moving points frequency per axis, which is defined as the inverse of moving points period per axis. Moving points frequencies are the same, whatever the axis. It means that, if distances between moving points are different for each axis, moving points have to move at different speeds according to their axis, in order to cover the distance between two consecutive moving points in the same time.

For the sake of readers, and without loss of generality, we adopt the two following conventions. Firstly, we suppose that the time needed to cover the distance between two consecutive intersection points on an axis is a multiple of the moving points period. Secondly, for each couple of axes i and j, phase difference is null. It means that, when a moving point from axis i is at the intersection of axis i and j, then a moving point from axis j is also present at this intersection.

IV. Approach to the Problem

In this section, we present the first work we have done on this problem. After some definitions, we deal with the link between the optimal solution of our problem and the structure of a graph that we introduce below, the conflicts graph. More precisely, we give lower and upper bounds on the quality of the optimal assignment.

A. Definitions

All the definitions below are illustrated by Fig. 1 to Fig. 4.

We call *intersections graph* the graph $G' = (V^I, A^I)$ where V' is the set of axes intersections. There is an arc between two vertices if and only if these two vertices are two successive intersections for one of the axes. This arc is valued by the number of moving points periods between the two intersections.

We call *conflicts graph* the graph $G = (V, E)$ where V is the set of moving points, and there is an edge between two moving points if and only if there exists an instant when these two points generate a conflict.

We now consider a cycle in the intersection graph. We call *cycle weight* the sum of the weights of the arcs that have the same orientation as the cycle, minus the sum of the weights of the arcs which direction is opposite to that of the cycle.

We call *cycle length* the number of edges in the cycle. We note m the smallest strictly positive cycle weight in an intersection graph, and L the associated cycle length.

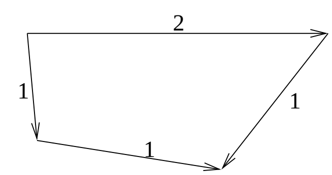

Fig. 3. Intersections graph (with m=1, L=4) for axis graph defined in Fig. 1

B. Results

Our main results exposed below deal with the relation between the $\frac{1}{k}$-density and the structure of the conflicts graph. Next theorem gives the exact characterization of ½-dense structures.

Theorem 1: There exists a ½-dense solution if and only if conflicts graph is bipartite and *(m+L)* is even.

This result is powerful as ½-dense solutions are the best solutions we can expect. It means that one moving point out of

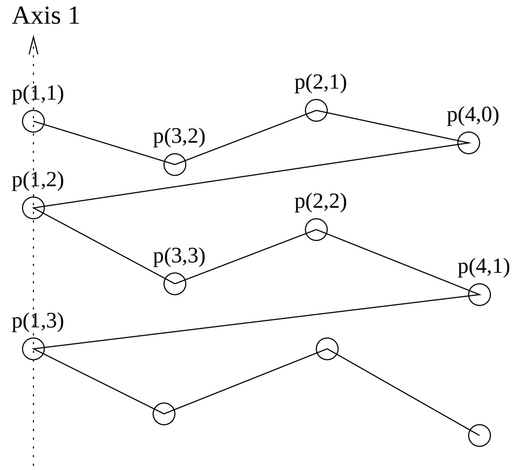

Fig. 4. Conflicts graph for axis graph defined in Fig. 1

two can be used in every axis. In addition we can notice that the occupation rate of each axis is 1/2 in any ½-dense solution. Actually, given an axis graph, if we know how to compute *m*, we are able to establish whether there is a ½-dense solution in a polynomial time, as bipartite problem is polynomial [5]. The only remaining difficulty is hence to compute *m*. We proved that *m* can be easily computed if we know the weight of every elementary cycle, but this problem is still non-polynomial.

It is well known that bipartite graphs correspond to 2-colourable graphs. We can extend theorem 1 to χ-colourable graphs:

Theorem 2: If there exists a $\frac{1}{k}$-dense solution, then conflicts graph is *k*-colourable.

Corollary: If conflicts graph is χ-colourable but not (χ-1)-colourable, the better expected solution is $\frac{1}{\chi}$-dense.

The corollary, which directly derives from theorem 2, gives a bound on the better solution we can expect. It is useless to try to find a solution better than $\frac{1}{\chi}$-dense if conflicts graph is not (χ-1)-colourable. For instance, if conflicts graph is not bipartite, the better solution we can hope for is a 1/3-dense solution.

Theorem 3: If conflicts graph is χ-colourable and if $m \geq \chi$, then there exists a $\frac{1}{2\chi - 1}$-dense solution.

This last theorem gives a worst-case bound if $m \geq \chi$. It guarantees that there is a $\frac{1}{2\chi - 1}$-dense solution for χ-colourable conflicts graphs with $m \geq \chi$. For bipartite conflicts graphs, it means that there is always a 1/3-dense solution, as long as $m \neq 1$. This bound is not tight for every value of χ, and we expect to improve it. Presently, we conjecture that there always exists a $\frac{1}{\chi + 1}$-dense solution for χ-colourable conflicts graphs with $m \geq \chi$.

V. CONCLUSION

This paper describes an air traffic paradigm, where aircraft are assigned to periodic moving points. The aim is to reduce aircraft energetic consumption and conflicts. Our problem is expressed as an optimization problem with constraints: we want to find an optimal allocation of the allowed/forbidden status to each moving point under the constraint that there are no conflicts (or very few) between each couple of allowed moving points in the subset of allowed moving points.

For the moment, we address feasibility issues, and more precisely bounds on the quality of the solutions. We first describe all the ½-dense solutions of our problem. We then expose a lower bound on the $\frac{1}{k}$-density: we show that we cannot expect solution to be $\frac{1}{k}$-dense if conflicts graph is not *(k-1)*-colourable. Finally we find an upper bound for the worst solution in the case $m \geq \gamma$, when conflicts graph is χ-colourable: there always exists a $\frac{1}{2\chi - 1}$-dense solution.

Future work is necessary to complete this work. First, the theoretical results are incentive to find operational subsets which satisfy the properties we proved. Moreover, we can test the influence of the first hypothesis we make. Actually, we presently assume that a 5NM-distance is necessary to avoid a conflict, but if aircraft are precisely assigned to moving points thanks to an automatic pilot, separation distance can be reduced. Finally we can expect to find other theoretical results, including a better worst-case bound than that in theorem 3.

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Ants-Inspired Dynamic Weather Avoidance Trajectories in a Traffic Constrained Enroute Airspace

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Abstract— **Weather is the single largest contributor to delay in the air traffic control system and is a major factor in aircraft safety incidents and accidents. However, most existing weather avoidance systems ignore the fact that weather is not static but changes dynamically through time. In this paper, we investigate the problem of finding dynamic weather avoidance trajectories in a traffic constrained enroute airspace. To avoid hazardous weather we make use of position, velocity and weather precipitation data and for traffic we use intent information. A state space is formed as a hyper-rectangular grid around the bad weather region. This grid stores the position and time information, i.e. 4-D, of weather cells as well as any traffic through it. Each cell of the grid forms a state in a graph. Each arc of the graph represents a possible transition from one state to another. This state space is then processed through an enumeration-and-elimination procedure to eliminate those states which have the estimated time of arrival of ownship and weather cells/traffic within a defined time window. The state transitions which violate aircraft performance envelop (turn & climb) are also eliminated. A heuristic search mechanism is extended to incorporate flight objectives (minimize heading change, altitude change, distance travelled) and to search the processed state space for multiple solution paths. To test the approach, we conduct experiments in an air traffic simulation environment with different weather patterns and conflicting traffic. Results show that our approach not only avoids the dynamically moving weather cells and conflicting aircrafts but also provides a set of route choices which are optimal on given flight objectives. Solution trajectories also show that clear pockets in weather patterns can be utilized to increase airspace capacity while maintaining aircraft safety. Finally, the approach shows that route choices in a constrained airspace may provide pilots with a desired flexibility in Free Flight. However, such advantage is limited by availability of decision support system for pilots and supporting infrastructure such as ADS-B and Doppler weather radars.**

Index Terms— **Air traffic management, dynamic weather avoidance, collision avoidance, ant colony optimization, intent based conflict detection**

I. Introduction

WEATHER is the single largest contributor to delay in the air traffic control system and is a major factor in aircraft safety incidents and accidents [1], [2]. Weather disturbances pose a serious threat for aviation on nearly a daily basis worldwide and they account for approximately 70% of all delays in U.S. National Airspace alone [3]. Even a small weather disturbance like rain fall can lead to water on runways which further lead to longer braking distance required by aircrafts. This further propagates to low acceptance rate of aircrafts by airport approach air traffic controllers, forcing the en-route air traffic controllers to circle flights in the air and delaying taking on flights from neighboring airspace. All these lead to delay propagation thousands of miles away resulting in grounded planes, canceled flights, higher fuel burns etc. [4]. Weather disturbances can also severely damage the airframe of the aircraft. They can potentially damage the navigational and electronic equipments leading to pilot's loss of control. During the enroute phase convective weather may appears as a cluster of convective weather cells and may block a jet route. This leads to aircrafts being shifted from one jet route to another causing congestion and reduced airspace capacity. However, narrow corridors still exist through which aircraft can pass. In Free Flight the pilots will have a larger role in real time route planning given airspace constraints such as weather and traffic [5]. Enroute aircrafts require a weather avoidance algorithm that takes into consideration multiple objectives besides avoiding weather cells of high severity. These objectives can be minimizing changes in heading, altitude while negotiating around weather cells and minimizing deviation from the planned trajectory. Further in the absence of jet routes in a Free Flight environment, the weather avoidance algorithm must also account for neighboring traffic such that the avoidance trajectory must not lead to possible collisions. The relatively fast changing nature of convective weather cells and neighboring traffic makes this a challenging problem.

Given the far reaching benefits to flight safety, fuel savings and capacity enhancement resulting from efficient weather avoidance systems, there has been a number of research and industry initiatives in this field.

The most significant of them in terms of research output and trials are Cockpit Weather Information (CWIN) and User Request Evaluation Tool (URET). CWIN [6] is a NASA and Honeywell Laboratory's joint initiative currently under development to distribute graphical weather information to the cockpit in near-real time. In an initial evaluation done for prototype CWIN weather avoidance tool by Dorneich et. al. [7], it was found that with the aid of a weather avoidance system there is a considerable increase in safety of a flight as well as significant fuel efficiency which was largely attributed to optimized weather avoidance routes. The MITRE Corporation's Center for Advanced Aviation System Development (CAASD) and the U.S. Federal Aviation

Administration (FAA) are currently developing a set of enhancements to the (URET) [8] to support the controller in severe weather situations and to assist the pilots in negotiating bad weather. The weather avoidance system utilizes the Dijkstra's Algorithm to compute the shortest path around the buffered severe weather polygons. This enhancement is in form of a severe weather display used in conjunction with Graphic Trail Planning (GTP) allowing controllers to enter vector maneuvers for severe weather avoidance into the Host computer, thus improving the quality of flight trajectories and increasing the likelihood that aircraft will receive the most efficient routes possible in severe weather situations.

Recently, Krozel et.al. [9] investigated the problem of synthesizing weather avoidance routes in the transition airspace using an algorithm based on the grid search method. They formalized the problem as a weighted regions problem in which routes obey Snell's Law of Refraction as a local optimality criterion. The generated weather avoidance paths were compared to three alternatives: variations of the Standard Arrival Routes, a geometric optimization solution synthesizing multiple non-intersecting routes, and two different Free Flight approaches in which aircraft fly weather avoidance routes using a greedy prioritization method. It was shown that an increase in airspace capacity is possible using efficient weather avoidance algorithms. However, this approach takes into consideration static weather cells only without any traffic. Moreover, the problem approach is single objective i.e. avoiding convective weather cells with no consideration of other flight optimization parameters.

Use of heuristics algorithms (A-Star) for weather avoidance in General Aviation was investigated by [10], the algorithm successfully computes the safest (in terms of weather) and shortest flight path around hazardous weather cells. However, the solution mechanisms do not undertake the optimality of solution and aircraft safety constraints and operates in a two dimensions abstract environment.

Prete and Mitchell [11] designed a Flow-Based Route Planner (FBRP), which computes routes for multiple flows of aircraft in the transition airspace using the A-Star algorithm. The planner allows for a variety of constraints on the computed routes based on type of aircraft, including hazardous weather patterns, turn and curvature constraints, and the horizontal separation standard. The algorithm searches for optimal routes within specified constraints using a search within a discrete network that models the geometry of the airspace. One of the key areas of extending the work as highlighted by the authors is of "having a set of optimal solutions to choose from, and to be able to search multiple routes in the presence of multiple airspace constraints".

Nilim et. al. [12] tackled the problem of dynamic convective weather avoidance for multiple aircraft flow management by using a stochastic dynamic programming algorithm, where the evolution of the weather is modeled as a stationary Markov chain. The approach provided a dynamic routing strategy for multiple aircraft that minimized the expected delay of the overall system while taking into consideration the sector capacity and traffic constraints. However, their system was limited to abstract modeling where the airspace was presented in 2-D and no physical constraints of aircraft, such as heading changes, acceleration/deceleration limit, speed, etc, were considered. Moreover, the approach could only minimize a single objective that of the distance traveled, without considering other flight optimization objectives such as altitude and heading changes.

Recently, Pannequin et. al [13] developed model predictive control based algorithm, which used the Hamilton-Jacobi equation to find the fattest trajectory for each aircraft subject to weather conditions, traffic constraints and wind profile. The algorithm could generate trajectories that avoid bad weather cells as well as potential collisions between aircrafts. However, their algorithm was limited to static weather avoidance, which did not take into account the dynamic changing nature of weather. Moreover, their system was centralized, in which information from all the aircrafts involving in the situation had to be fed into the algorithm so that the system could compute their trajectories. This centralized design suffered from limited scalability and poor robustness, as well as were subject to equipment failure at the Air Route Traffic Control Center level.

Most existing weather avoidance systems/ algorithms do not take into account the dynamic nature of convective weather pattern in the high-fidelity realistic flight environment, which takes into consideration the flight performance parameters as well as multiple flight optimization objectives. As identified by Krozel et. al. [14], "...a key evolution of future air traffic management system in weather avoidance is to dynamically assigning routing to aircraft and adjusting the routes to the size and shape of weather constraints as they change".

The key objectives that we identified in developing weather avoidance algorithm for enroute traffic constrained airspace are:

• It must be able to search multiple routes in the presence of multiple airspace constraints which include relatively fast moving convective weather cells and neighboring air traffic.
• It should accommodate flight optimization objectives such as minimizing changes in heading, altitude and deviation from planned trajectory.
• It must take into consideration aircraft performance parameters.
• It must be able to generate weather free trajectories such that there is no loss of separation with neighboring traffic.
• It should provide the set of optimal solutions to choose from.

In this paper, we present a weather avoidance algorithm which is conceptually based on space-time search using a combination of two heuristic search mechanism viz. Ant Colony Optimization, a meta heuristic search technique inspired by functioning of real ants and A-Star which is an informed heuristic search technique. In a later section we describe them in detail and how we adopted them to suit our problem domain. We have used our in-house Air Traffic Operations & Management Simulator (ATOMS) [15], to create bad weather scenarios and to simulate air traffic.

The paper is organized as follows, in the next section we explain the weather avoidance problem and state space pre-processing mechanism followed by the design of the algorithm using ACO and A-Star. We then explain the experimental design and conclude with the results and discussions.

II. Algorithm Design

Finding weather avoidance trajectories can be seen as path planning in four dimensions (i.e. time and the physical 3-D space). In air traffic management this problem attains unique dimensions due to safety and airspace constraints posed on it. Apart from the hard safety constraints like aircraft performance envelop (turn and climb) and potential conflicts the objectives are to minimize severe weather cells impact, minimize changes in heading, minimize changes in altitude (climb and descent), and minimize the deviation from the planned trajectory. We will first formulate the problem for avoiding dynamic weather cells and then extend it to traffic avoidance.

A. Problem Search Space

The weather cells can spread in an area extending up to 1000 square nautical mile [16]. Finding feasible solutions in such a large search space can be damning from safety and time perspective. Hypothetically, if the number of states in the search space can be reduced without compromising the solution quality, the reduction of state space size will result in faster convergence.

By pre-processing infeasible transitions in the search space, the search is guaranteed to produce feasible solutions. We eliminate the state space recursively starting from an entry point in the 4-D grid and doing forward recursion on different layers. At each layer we eliminate states which violate the problem constraints before moving to the following layer.

Thus, we can guarantee that the resultant state space contains feasible transitions only.

B. Problem Constraints

The following safety constraints are considered in the algorithm design:

1) Performance constraints: These constraints include restrictions based primarily on the operating limitations of the aircraft. Restrictions, such as maximum operating altitude, climb/descent rate, and maximum permissible turn, govern the degrees of freedom available for weather cells avoidance maneuvers.

2) Airspace Hazard Constraints: These hazards are present in the airspace when a particular region is inaccessible for maneuvering, either reserved for Special Use (SUA) or that a particular maneuver may lead into conflict situation with other neighboring aircrafts in the airspace. In this paper we consider neighboring traffics as a hazard constraint.

C. Objectives

The following objectives are considered in the algorithm design:

1) Avoid weather cells: The prime objective of the algorithm is to avoid bad weather cells, especially those with high precipitation (radar reflectivity). If there is no possible path through the bad weather cells within the search founds, the algorithm finds the trajectory which passes through weather cell(s) with least precipitation.

2) Minimize deviation from flight plan: Another objective of the algorithm is to find paths which satisfy the constraints and have the least deviation from the original planned trajectory.

3) Minimize heading changes: Solution trajectories that involve too many heading changes will cause higher fuel cost as well as discomfort to the passengers. This may lead to degradation in aircraft performance as the aircraft may not be able to follow sharp turn angles due to "start of turn distance" limitation.

4) Minimize climb and descent maneuvers: In mature stage the weather cells shows high tendency of upward and downward drafts with lightening. These drafts some- times reach high wind speed of 8000ft to 10,000ft per minute. Flying above or below a thunderstorm cell by climb or descent maneuver is never advisable. Thus solution should minimize changes in the altitude.

D. Problem definition

The problem can then be stated as follows: Given a 4-D grid of dimensions i (latitude) x j (longitude) x k (altitude) and time t, an entry point x (start manoeuvre point) and an exit point y (end manoeuvre point), locations of weather cells and their severity in space and time in this grid find the set of routes between x and y on the given objectives satisfying the problem constraints.

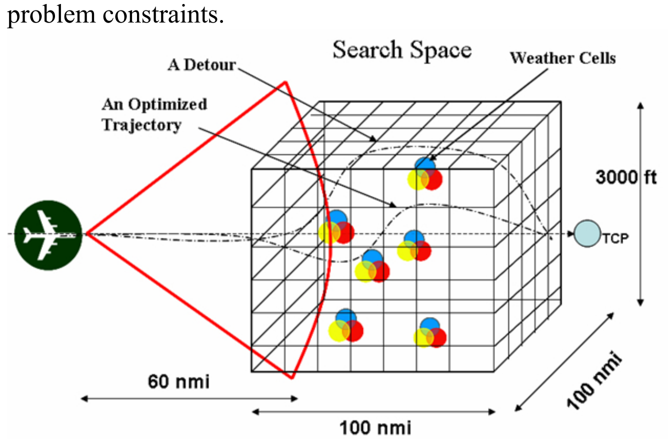

Fig.1. Conceptual representation of weather avoidance algorithm design

Weather cells were simulated in the enroute airspace by assigning a radar reflectivity (a measure of thunderstorm intensity) value between 5 and 50 by using a uniform distribution random number generator. All weather cells were dynamic in nature and have speed and direction. Each cluster of bad weather cells comprises of 6 to 12 thunderstorm cells of dimension 10 nmi X 10 nmi X 3000 ft [17]. As shown in figure 1, the algorithm upon detection of weather cells at a distance of 60nm, (weather radar range) generates a three dimension volume around them. This airspace volume is of dimension 100 nmi X 100 nmi X 3000 ft.

This search space is then discretized in a grid of 10 x 10 x 3 (300 nodes), which gives enough volume (1000 sq nautical mile) to cover the entire weather pattern. Each cell in the grid forms a state in the graph. The arcs of the graph represent possible transitions from one state to another. The state space is then processed for aircraft performance constraints. This performance constraint data for the given aircraft is derived from the Eurocontrol's Base of Aircraft Data (BADA) [18] aerodynamic model.

To take into account the dynamic characteristic of the weather, the 3-D grid is extended to 4-D by including time as the fourth dimension. The simplest way to encode the time dimension is to take a snapshot, i.e. aircraft positions and weather cells' positions and intensities, of the discretized grid at every time step. However, since the rate of change Δt of the grid is limited by the minimum time that takes either a weather cell to move from a node i to the next node j or an aircraft to move from i to j, snapshots of the 3-D grid at time intervals Δt are recorded. The time $t_w = \frac{d_{ij}}{V_W}$ for a weather cell to move from node i to node j is limited by the speed V_W of the weather cell and the distance d_{ij} between nodes i and j. Similarly, the time $t_A = \frac{d_{ij}}{V_A}$ for an aircraft to move from node i to node j is limited by the speed V_A of the aircraft and the distance d_{ij} between the two nodes.

$$\Delta t = \min(t_w, t_A) = \min\left(\frac{d_{ij}}{V_W}, \frac{d_{ij}}{V_A}\right) \qquad (1)$$

The resultant 4-D grid is stored in a 4-D array data structure as an enumerated state space where each element of the array represents a point in the 4-D grid. Every array element stores the information about its snapshot index and position (latitude, longitude and altitude) and all the immediate next links (which do not violate aircraft performance envelop) from that point in the grid. Furthermore for each link, the array element stores the heading change required, altitude change required, distance between the two nodes and the distance to exit point from that link. The search algorithm performs search on this pre-processed state space.

E. Traffic Constraints

The above concept is extended to take into account the neighboring traffic that might have potential conflicting trajectories with the weather avoidance routes. The 3-D airspace in ATOMS is divided into hyper rectangular 4-D grid structure. Every cell in the grid acts as a repository of information for the flights that passes through it. The information apart from call sign includes the estimated entry time and estimated exit time of an aircraft in that cell. When a flight is initialized (flight plan loaded into the system's memory), based on its intended trajectory, all the grid cells through which the trajectory passes are updated with the flight information. This information is updated/deleted wherever the aircraft changes its trajectory or passes by a cell in the airspace grid. We assume that all the aircrafts are ADS-B [19] equipped where they broadcast/receive state and intent information to/from the neighboring traffic.

Once the weather free routes are computed, they are converted into grid-cell plans which will be traversed if a particular route is chosen. If the estimated time of arrival (ETA) of the weather avoiding aircraft and of the traffic aircrafts, at a given cell common in their trajectories, is within five minutes (based on average speed of transport aircraft of 300nm, and 10 nm distance between two neighboring cells in the grid), a collision is signaled and the route is discarded from the solution set.

As conceptually shown in Figure 2, the solution set contains two possible paths which avoids weather cells. The ETA of each path and the traffic passing through the weather grid are checked. The solution path that consists of cells where its ETA and the ETA of the traffic is less than 5 minutes is discarded.

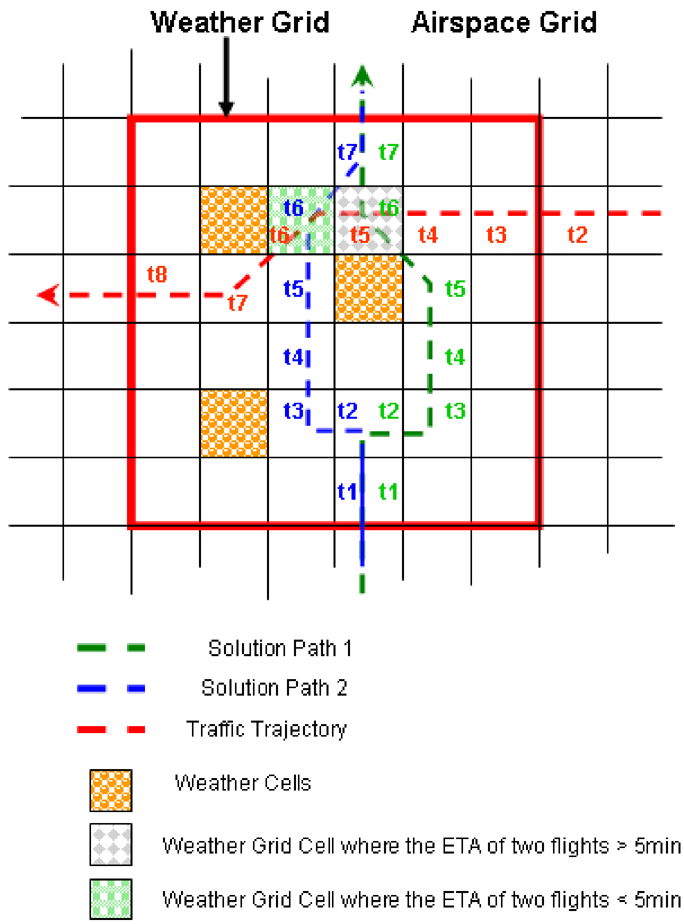

Fig. 2. Possible paths with ETA of each path and traffic passing through the weather grid

III. SEARCH ALGORITHM

We have combined features of meta heuristic search techniques (ACO), to leverage upon their exploration nature, and informed heuristic search techniques (A-Star), to leverage upon their exploitation nature. These heuristic search algorithms were employed as they have shown several desirable properties for application in the transportation domain [20].

A. A-Star

The A-Star [21] algorithm is an informed heuristic search

technique which minimizes the estimated path cost to a goal state (destination). At a given node n, the A-Star algorithm will choose the next state which minimizes the function *ϒ(n) = g(n) + h(n)*, where *g(n)* gives the path cost from the current node i to the next node j, and *h(n)* is the estimated cost from the next node j to the destination node (exit point).
We define the heuristic function *g(n)* as the estimated cost on weather severity (WF), heading change (HF) and altitude change (AF) from current node to next node and *h(n)* as the estimated distance (DF) from the next node j to the exit point in the search grid. The next-node distance cost is not incorporated in *g(n)* as all neighboring nodes will be equidistant from current node given the grid structure.

$$\Upsilon(n) = (w_1\,WF + w_2\,HF + w_3\,AF) + (w_4\,DF) \tag{2}$$

where w_1, w_2, w_3, w_4 are dynamically initialized polar weights on the surface of a unit sphere [7].

B. Ant Colony Optimization

The ACO algorithm [22] is a meta-heuristic search technique for finding solutions to hard combinatorial optimization problems. The paradigm is based on the foraging mechanism employed by real ants attempting to find a shortest path to a food source. Ants use indirect communication via the environment by employing pheromone trails. In ACO, the transition rule which is the probability for an ant k on node i to choose next node j while building its path is given according to the following rule:

$$j = \begin{cases} \arg\max_{u \in J_i^k} [\tau_{iu}(t)] \times [\eta_{iu}]^\beta & if\ q \le q_0 \\ J & f\ q > q_0 \end{cases} \tag{3}$$

where $J \in J_i^k$ is a node that is randomly selected according to the following probability

$$p_{ij}^k(t) = \frac{[\tau_{ij}(t)] \times [\eta_{ij}]^\beta}{\sum_{J \in J_i^k} [\tau_{ij}(t)] \times [\eta_{ij}]^\beta} \tag{4}$$

where τ_{ij} is the pheromone value between the two nodes and j, controls the relative weight of η_{ij}, and is a random variable uniformly distributed over [0,1].
Parameter q_0 in equation (2) is a tuneable parameter ($0 \le q_0 \le 1$), where q_0 corresponds to an exploitation of the heuristic information of given objectives and the learnt knowledge memorized in terms of pheromone trails, whereas $q > q_0$ favors more exploration of the search space. We tune this parameter in the interval [0,1], to evolve different search behavior.
The visibility parameter η_{ij} in equation (3) represents the heuristics desirability of choosing node when at node i, it can be used to direct the search behavior of ants by tuning in the interval [0,1]. We have incorporated the inverse (since it is a minimization problem) of the A-Star evaluation function *ϒ(n)* for the visibility parameter η_{ij} of the ACO.

$$\eta_{ij} = \frac{1.0}{\Upsilon(n)} \tag{5}$$

The solution trajectories generated by the search algorithm are converted into actual flight routes with artificial waypoints (Figure 3). These optimal trajectories can then be prioritized by the flight management system (FMS) based on pilot's preference. The flight plan is then amended where the modified section of the route based on the chosen solution trajectory is fed into the FMS which then fly the aircraft in auto-pilot mode and follow the updated route.

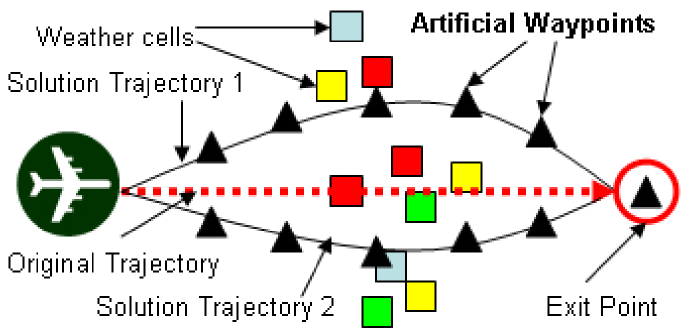

Fig. 3. Flight routes with artificial waypoints generated by the ACO-based Weather Avoidance algorithm.

IV. Experiment Configuration and Results

ATOMS is employed to generate weather patterns and traffic scenarios. Middle-east airspace (OBBI FIR) is used for weather modeling and flight simulation. Flights from OERK to OKBK and in the opposite direction are simulated with great circle routing between its origin and destination. The cruising altitude is set to 27kft for the flights. Two different enroute weather patterns are simulated: clustered weather cells and distributed sparse weather cells 4. The weather cells are generated with a constant wind speed of 60kts (30m/s) and a direction of 2 degrees from the true North. These weather patterns are activated to obstruct the intended trajectory of the flights.
We tested the algorithm in two different situations: (A) an aircraft flies through bad weather cells that are dynamically changing through time, and (B) two aircrafts, with head-on conflict, fly through dynamically changing bad weather cells. In the first situation, the algorithm has to find a set of solution trajectories that avoid any severe weather cell impact. In the second situation, the algorithm has to find a set of solution trajectories, which not only avoid the bad weather cells impact but also avoid conflicts between aircrafts. By conflict, we mean that at any time during the weather avoidance maneuver, the two flights are at least 5 nm horizontally and 1000 ft vertically separated from each other. All the generated flight paths have also to satisfy the aircraft performance constraints.

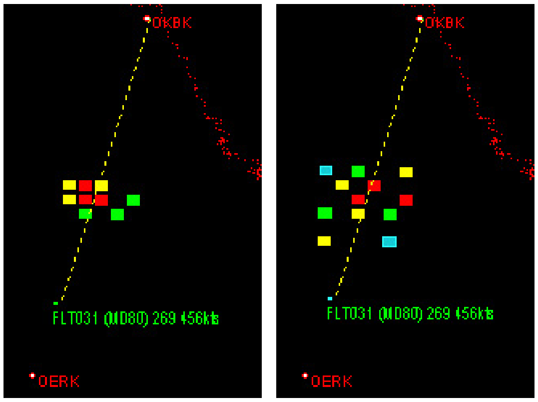

Fig. 4. Snap shot of the different weather scenarios in the flight path (dotted lines) of an aircraft. Left: clustered weather cells, right: distributed sparse weather cells.

A. *Dynamic weather avoidance without traffic constraint*

The algorithm generated 322 possible routes which are weather impact free in the given scenario. All the routes are optimum on the given objectives and within the aircraft performance parameters. Figures 5 and 6 present a series of snapshots, in terms of time, of flight FLT031 (OERK to OKBK) through two different weather scenarios. The snapshots show one of the optimized weather-free trajectories generated by the algorithm through bad weather cells when the cells are moving dynamically. The search space is drawn as the dotted grid around the weather cells.

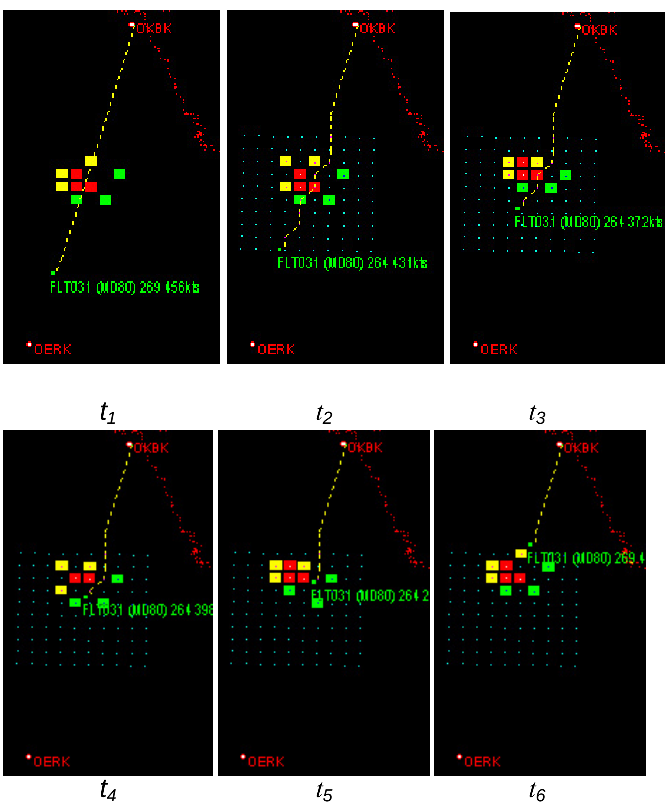

Fig. 5. Clustered Weather Scenario: Snapshots (time progression t1→ t6) of flight FLT031 through dynamically moving bad weather region.

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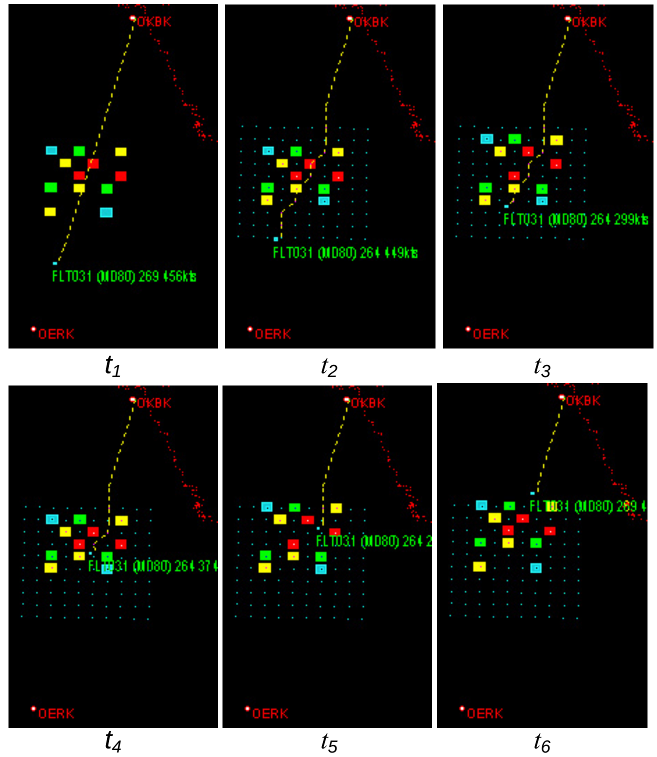

Fig. 6. Distributed Weather Scenario: Snapshots (time progression t1 t6) of flight FLT031 through dynamically moving bad weather region.

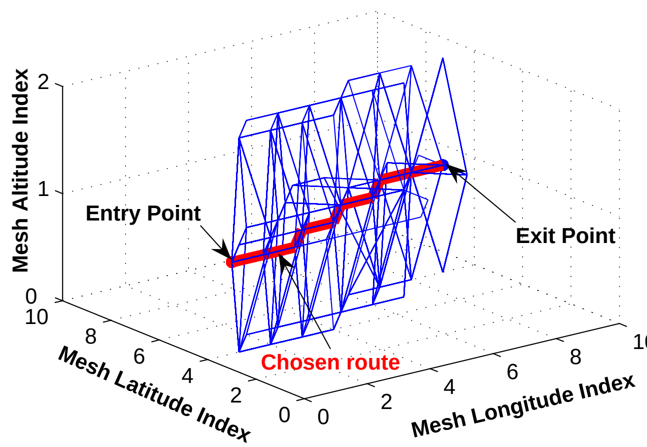

Fig. 7. 322 weather-free routes generated by ACO. The thicken line represents the chosen flight route.

Aircraft Performance Constraints: For the selected trajectory which was flown by the aircraft we examined the performance constraints from safety perspective. For the given *MacDonnell Douglas-80* aircraft (MD80) we plotted its rate of accelerate-decelerate (ROAD), rate of climb and descent (ROCD) and rate of heading change (ROHC) for the given maneuver.

Figures 8, 9, 10 shows that aircraft maneuvers were within the bounds of its performance envelop.

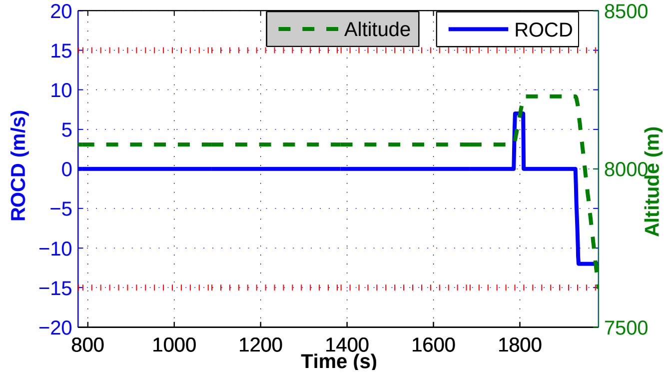

Fig. 8. Altitude and Rate of Climb/Descent of FLT031 via dynamic bad weather region. Boundary lines represent the aircraft performance envelop (max/min ROCD = ±15m/s)

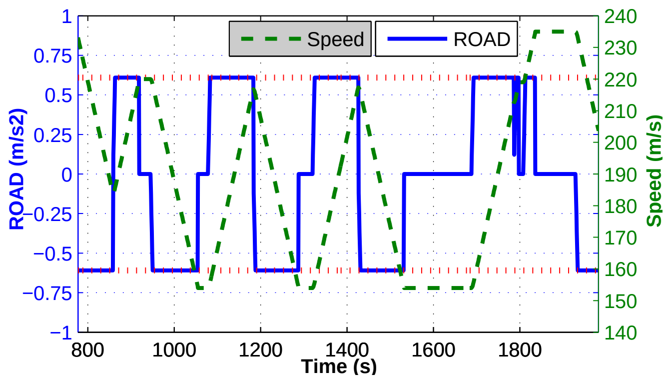

Fig. 9. Speed and Rate of Acceleration/Deceleration of FLT031 via dynamic bad weather region. Boundary lines represent the aircraft performance envelop (max/min ROAD = ±0.7m/s2)

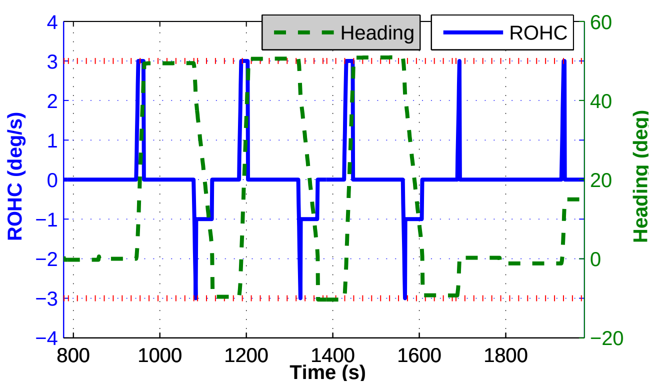

Fig. 10. Heading and Rate of Heading Change of FLT031 via dynamic bad weather region. Boundary lines represent the aircraft performance envelop (max/min ROHC = ±3degree/s)

B. *Dynamic weather avoidance with traffic constraint*

Figure 11 presents the snapshots of two potentially head-on conflicting flights, both passing through the bad weather region. The algorithm can generate solution trajectories that avoids bad weather cells as well as maintain safe separation distance between the aircrafts.

The sequence of events of detection and avoidance happens as follows:

1) FLT031 detects the weather cells and uses the weather cell information and intent information of FL032 to generate the weather and traffic avoidance trajectory.

2) FLT031 updates its flight plan and propagates intent information.

3) FLT032 detects the weather cells and uses the weather cell information and updated intent information of FLT031 to generate the weather and traffic free route.

4) FLT031 and FLT032 fly through weather cells without encountering one and maintains safe separation from each other.

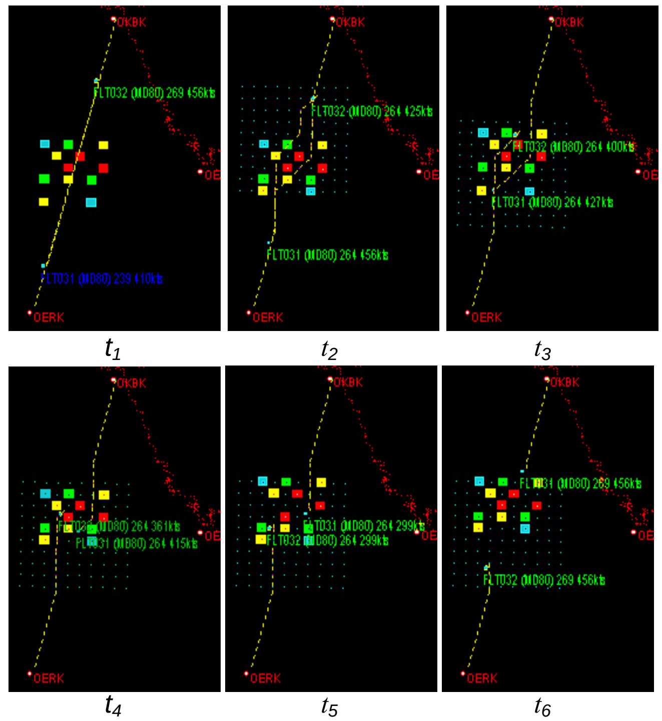

Fig. 11. Distributed Weather Scenario: Snapshots (time progression t1 → t6) of potentially conflicting flights FLT031 & FLT032 via dynamic bad weather region.

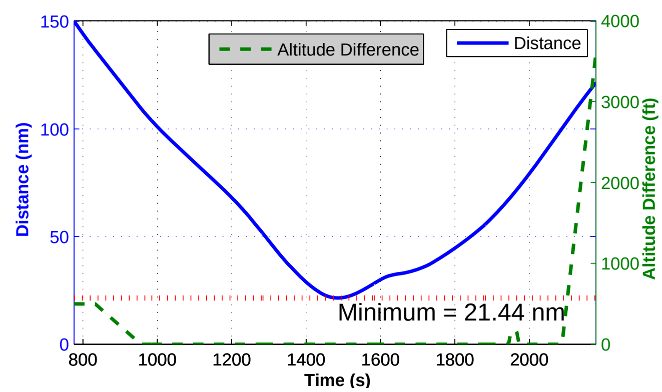

Fig. 12. Horizontal and vertical seperations between two aircrafts, FLT031 & FLT032 avoiding the bad weather cells. Minimum horizontal separation is 21.44nm

Figure 12 shows the horizontal and vertical separation between the two aircrafts during their maneuvers. As shown, the minimum horizontal separation between the two flights during the maneuver is 21.44 nm. In other words, the algorithm can generate weather avoidance and collision free trajectories in a traffic constrained airspace. Currently, we have tested the algorithm for simple traffic constraints (head-on conflict scenario including two aircrafts). In the future, we are planning to extend the weather avoidance algorithm in challenging traffic constraints involving multiple aircrafts.

V. DISCUSSIONS AND FUTURE WORK

A safety inherent design utilizing intent information can provide a good framework for weather avoidance problem in an enroute traffic environment. Pre-processing the state space before search helps in reducing the search space and making the search manageable. Heuristic search provides a good mechanism for incorporating multiple objectives and combining the virtues of exploration of environment and exploitation of information available about the environment. The algorithm generates a set of solution trajectories in different weather patterns in a traffic constrained airspace successfully. All the trajectories were optimal on the given objectives. Moreover, the trajectories generated were all flyable, such that they do not compromise the performance envelop of the aircraft.

On the downside, since the algorithm takes into consideration the performance parameters of an aircraft, which restrict the turn angle for heading change and bank angle for vertical maneuver, it may not generate optimum avoidance trajectories if the aircraft is very close to weather cells at the time of detection. Finally, the algorithm performance is based on the assumption that the traffic intent information and weather cells information, which is provided through ADS-B transmission and on-board Doppler radar respectively, is available and error free. We will be testing our algorithm with high density enroute traffic and investigate the system level performance of the algorithm.

ACKNOWLEDGEMENT

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EGPWS on Synthetic Vision Primary Flight Display

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***Abstract*— This paper describes flight tests of a Honeywell Synthetic Vision (SV) Primary Flight Display prototype system integrated with Enhanced Ground Proximity Warning System (EGPWS). The terrain threat information from EGPWS system is displayed with synthetic vision terrain background in a coordinated 3D perspective-view and 2D lateral map format for improved situation awareness. The flight path based display symbology provides unambiguous information to flight crews for recovery and avoidance with respect to the threat areas. The flight tests further demonstrate that the SV based display is an effective situation awareness tool to prevent crew blunder in low visibility situations and further backup the accident chain that typically proceeds control flight into terrain (CFIT) accidents.**

***Index Terms*—3D Terrain, PFD, Symbology, Synthetic Vision, EGPWS**

I. Introduction

THE advancement in synthetic vision primary flight display systems has led to Part 23 certification for general aviation aircraft [1] and more recently announcement of product introduction into high-end business aviation aircrafts by Honeywell Aerospace [2]. Such a major step forward to bring a new safety enhancement technology into demanding business aviation applications is the result of significant research and development efforts at Honeywell [3] and maturity of a number of underling technologies such as EGPWS systems [4], and large-format, full-color, sunlight-readable flat-panel-displays similar to the ones used in Honeywell Primus Epic™ integrated avionics systems [5]. With an extensive research and development knowledge base [6-8] and gradual introduction of such systems into a wide array of aircraft platforms, SV primary flight display systems are expected to provide both improved safety, operational benefits at various phases of flight, reduced training requirements, and more integrated displays for control and navigation applications with reduced work load.

Honeywell Aerospace has taken an approach of developing a SV integrated primary flight display system (IPFD) by leveraging a number of well established avionics subsystems such as Honeywell HUD2020 head-up display symbology sets and the proven EGPWS worldwide terrain database. The EGPWS systems and terrain databases are installed on thousands of aircraft worldwide, and have logged more than 750 million flight hours. The prototype SV IPFD system uses the EGPWS terrain database to render 3D perspective terrain background and geometric altitude to position the 3D terrain environment in order to eliminate possible altimetry errors caused by incorrect barometric altimeter settings, atmospheric extremes, and low transition altitude operations [4]. This is an important safety consideration given 25 percent of all CFIT accidents have certain contributing barometric errors as shown in the study by D. Bateman [9]. Given the compelling nature of the perspective-view SV presentation coupled to a flight path based symbology, these types of errors can cause hazardously misleading information when presented to flight crews.

EGPWS systems typically display terrain and obstacle threats visually on a 2D map, and further provide aural callouts for terrain or obstacle alerts. Potentially hazardous terrain and obstacle areas can be displayed more intuitively on a perspective view primary flight display relative to the current flight path, which can lead to improved avoidance and recovery maneuvers. In addition, with perspective terrain view for situation awareness, the flight crews could detect and visualize the potential conflicts earlier, further reducing the likelihood of entering the flight envelope to trigger the caution and warning events.

This paper describes the flight tests of integrating EGPWS caution and warning information into Honeywell's prototype SV primary flight display system with the threat information shown relative to the current flight path. A coordinated 3D perspective view and 2D map format is used to provide look ahead and strategic views for visualizing threat information. We will demonstrate that such a display format is beneficial to pilot decision making processes when executing avoidance maneuvers and provides a more intuitive display for extended conflict detection lead time.

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II. Flight Tests Overview

A. Hardware Installations

The flight test hardware was installed on a Honeywell Citation V Aircraft, as shown in Figs. 1 and 2. The left side cockpit panel was modified to fit a Honeywell Primus Epic™ DU1310 display unit (11.3 x 8.5 in) to present a coordinated 3D perspective view PFD with a 2D lateral map to a flying pilot, as shown in Fig.2. A Honeywell Primus Epic™ CDS/R DU1080 EFIS display was installed on the right side of the cockpit. The aircraft was equipped with Honeywell ADS-AZ252 air data computer system (ADC), a Laser Ref V ring laser gyroscope-based inertial reference system (IRS), and GNSSU-HG2021-GD-02 global positioning system (GPS). For test purposes, the SV display was driven by a modified personal desktop computer located in the aft cabin. The same test computer was used to read ADC, IRS, and GPS sensor data available on an ARINC 429 bus and to process raw sensor data in order to produce smooth PFD symbology displays and real-time moving synthetic view terrain images.

Fig.1 Honeywell Citation V flight test aircraft

To display terrain threat information from EGPWS, the test computer was connected to a modified on-board MARK VII EGPWS unit via a direct ARINC 429 data link. The EGPWS unit continuously sent out data frames containing aircraft-position-referenced data grids with threat information encoded at the grid locations. The threat patterns were produced based on the EGPWS computations taking into account position, track, altitude, terrain profiles, speed, etc. [4]. The test computer continuously acquired and processed the incoming data frames. When the frames contained threat information, the color-coded threat levels at corresponding locations were immediately displayed both on the perspective view and the map displays. The test system exhibited minimal data transmission delays after the EGPWS system aural callout such that proper tests could be conducted to evaluate the threat displays on the perspective view PFD.

Fig.2 SV PFD display cockpit installation

EGPWS integration tests are usually conducted as part of overall flight tests during Honeywell SV PFD development. The test setups in Fig.2 were therefore constructed to accommodate a variety of test profiles. For example, a control panel was installed by the side of the DU1310 display unit for pilot to select display settings for altitude, heading, speed, track, and to adjust 2D navigation map range. These settings were sent to the test computer and were displayed on the PFD. The small 2D navigational map insert was provided to test pilots at the lower right corner of the PFD as the modified cockpit panel would not allow installation of a separate, larger navigational display. Test pilots were able to control the display range of the 2D map during normal flights via the control panel. During an EGPWS threat event, the area of threat was color coded yellow (caution) or red (warning), and the 2D map was automatically ranged to ensure full view of the threat area around the present position. The same test computer recorded relevant aircraft flight data and EGPWS data frames into replay files for post flight analysis. Subjective data were collected during the flights via verbal comments. Flights were digitally recorded with cameras for the out of window views.

B. Test Flights

Local flights included a departure from Deer Valley Airport (DVT) in Phoenix, Arizona, and scripted scenarios including enroute air work to Flagstaff, Arizona (FLG), and/or Sedona, Arizona (SEZ). In addition to the local flights, cross-country flights were conducted to targeted terrain challenged airports including IMC approaches at Aspen, Colorado (ASE), day and night approaches into Reno, Nevada (RNO), coastal fog IMC approaches into Santa Barbara, California (SBA) and marginal VFR approaches to Asheville, North Carolina (AVL). Various test scenarios were conducted during flights to evaluate symbology performance, terrain appearance, EGPWS caution and warning displays, etc. Part of the EGPWS integration tests conducted at different locations across the country will be presented and discussed.

III. Terrain Threat Display

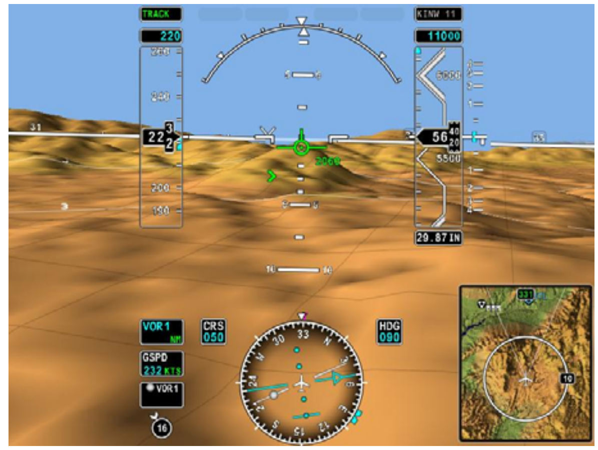
The nominal Honeywell SV prototype display consists of the primary attitude symbology such as airspeed and altitude tapes, zero-pitch reference line, pitch scales, roll indicator, and heading indicators, as shown in Fig. 3. This display screen capture in Fig. 3 and subsequent figures were generated with the actual flight test data recorded near Las Vegas in April of 2005. The flight path marker symbology group (FPM, acceleration cue, and radar altimeter output) is displayed similarly as on the Honeywell HUD2020 display. The display is centered either in a track or hybrid (combines elements of track and heading) mode to clearly depict aircraft movements relative to the terrain ahead with altitude information provided by an EGPWS geometric altitude input. The advantages of such centering modes include unambiguous display of aircraft direction of travel and stability for controlling the aircraft, as discussed in our previous studies [10-11]. The EGPWS threat information is overlaid onto the terrain with yellow as caution areas and red as warning areas. Here, the areas of coloration are determined by the data frames sent over from the on-board EGPWS unit, as described in Section 2. When displaying threat information, the terrain relief features are embedded into the threat level colorings in order to maintain a consistent sense of perspective distance and motion cue. The perspective terrain tracing range rings in the display provide a direct distance measure to the threat areas. A text annunciation matching aural callout is displayed when a threat event occurs. For a warning event, the PULL UP annunciation is prominently shown on the top portion of the display to indicate the command. As shown in Fig.3, the flight path marker clearly depicts where the aircraft is going relative to the terrain threat areas. When the flight path marker is positioned above the terrain, the aircraft's flight path is projected to clear the terrain although the present position may still be below the threat terrain elevations. It is noted that yellow and red colors are reserved for caution and warning events and are applied to the threat terrain areas as determined by the EGPWS system. This is different from situation awareness displays where terrain is color-coded as shades of yellow and red for the portions at or above the aircraft position and shades of green for the portions below the aircraft position. Such color usage for situation awareness is deemed to be highly distractive in the PFD mode during our flight tests and is considered redundant, since the relative positioning of the terrain profile ahead is clearly and intuitively shown on the perspective PFD with the terrain portions that are above and below aircraft are displayed above and below the zero-pitch reference line respectively. Therefore, the Honeywell prototype IPFD implementation was able to reserve the use of yellow and red colors for threat event related terrain areas.

Fig.3 EGPWS warning and caution integrated IPFD display

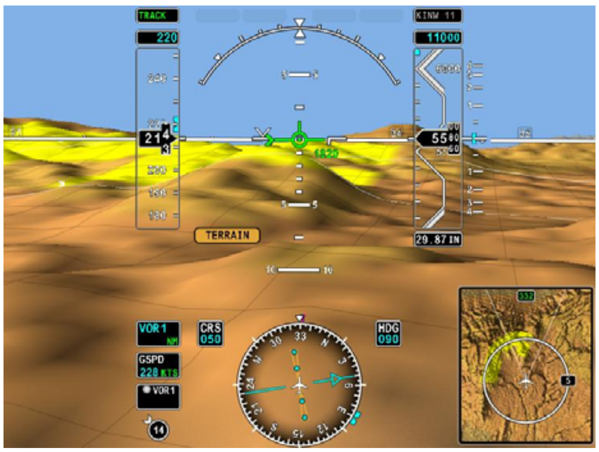
In Fig.4, the recorded test sequence which led to the terrain warning event is depicted with initial turning into and aiming at the terrain feature defined as the time zero when the terrain feature was about 10nm away from the aircraft's current position, as in Fig.4 (a). After test pilots held the course and flight path aimed at the terrain features for an additional 73 seconds, the terrain feature was less than 5nm from the present position and the 3D perspective display shows clearly where the aircraft is aiming at and where the potential terrain conflicts are expected to be, as shown in Fig.4 (b). In comparison, the 2D map does not convey such clear conflict prediction images. In Fig.4 (c), after the test pilots (intentionally) maintained the present course for an additional 24 seconds (97 seconds after turning toward the peak), the first of a series of terrain caution alerts was displayed after the aural callout. After an additional 28 seconds on the same track, the first of a series of warning pull-up callouts was displayed.

The sequence shown in Fig.4 demonstrates that the IPFD display clearly shows where the potential conflicts will be for the current flight path well ahead of triggering EGPWS events. It therefore offers an increased lead time for conflict detection thus reducing the likelihood of operating an aircraft into such flying envelopes during low visibility conditions. Secondly, the flight path based symbology displayed with the terrain threat areas shows the recovery path clearly for the current flight conditions with the primary recovery maneuver being full-power pull-up.

(a) Time = 0 seconds



(b) Time = 73 seconds



(c) Time = 97 seconds, caution

(d) Time = 125 seconds, warning

Fig.4 Test sequence to trigger terrain warning event

IV. Obstacles Threat Displays

The obstacles are displayed in the SV PFD prototype as a semi-transparent fixed-width polygon strip under normal conditions, as shown in Fig.5 (a). This display format is designed to provide sufficient awareness of obstacles ahead while meeting the basic requirements of not degrading primary flight attitude data display and minimizing clutter. The screen clutter is of particular concern when approaching a runway as the number of obstacles can be significant around an airport area near the approach path. When obstacles become threats, the obstacles and surrounding terrain areas are colored according to the threat levels and the obstacles are displayed as wider solid polygons with corresponding threat colors of yellow for caution and red for warning, as shown in Fig. 5(b). The obstacle threat data are similarly transmitted from the on-board EGPWS unit to the flight test computer and are processed to display the corresponding threat levels at the locations from the threat data.

Both Fig.5 (a) and (b) are generated with the flight test data recorded near Asheville, North Carolina in April of 2005. During the tests, pilots flew toward various obstacles to trigger EGPWS caution and warning events. Test pilots would maintain the course for an extended period of time in order to trigger such events. The obstacles generated with an on-board obstacle database were often visible on the PFD displays well before they were visually spotted during the tests. These tests demonstrate that such obstacles displays in the perspective view mode provide added lead time in obstacle conflict detection. Although obstacle displays based on database will be limited by the obstacle information contained in the database (e.g., type and dimensions), it is highly valuable for low-visibility approach operations to prevent the types of accidents of colliding with these known structures around the approach path.

V. Flight Test Results

The results from this series of flight tests were very positive regarding the utility of the integration of EGPWS caution and warning alerts on the synthetic vision Primary Flight Display in the pilot ego-centric frame of references. The alert areas with terrain shading contributed to extremely positive subjective ratings collected in the post-experiment questionnaire with regards to the presentation format. In addition, the color coding of the rendered obstacle strip in addition to the terrain patch was deemed desirable when the alert patch included obstacles.

(a) Normal obstacle display (b) Obstacle caution

Fig. 5 IPFD obstacles displays

Sample written pilot comments collected in the post-experiment questionnaire include:

- The terrain/obstacle display rendering was my favorite part of the display -- much more intuitive and unambiguous than current TAWS
- The database is excellent and integration with obstacle and alerts was well done
- The tower (obstacle) fly by demo and alert was very impressive. This feature is very important for helicopter operations.
- The integration of EGPWS alerts was well done, but it is doubtful I would ever see in operations because of the extreme intuitiveness of your synthetic vision display. I will turn away long before an alert happens.

Although not demonstrated in the present flight test evaluations, it is conceivable that an EGPWS alert could occur outside the field of view of the SVS display. In that situation, with the current IPFD prototype, the text message and aural alert would appear along with the visual alert areas on a 2D display, but there would be no yellow or red terrain patches on the perspective view IPFD. In addition, in today's EGPWS system, there is a radio altitude mode of EGPWS alerts (i.e., the GPWS alerts) that do not rely on terrain database. Therefore there is no patch of terrain that is color coded on IPFD or the EGPWS displays.

VI. Display of Airborne Traffic

Preliminary flight tests have begun to integrate traffic into the synthetic vision Primary Flight Display (see Fig. 5). There are several issues that need to be addressed in terms of position accuracy required and update rates. To date the results have been promising and are planned to continue. One human factors issue that has been addressed is the inclusion of a drop line from the aircraft symbol to the point on the ground it is over to assist in recognizing its distance from your own aircraft. In addition it utilizes the standard TCAS symbology and color codes to simplify transfer of training between these systems. When fully developed the display could significantly enhance the situation awareness of flight crews flying on dense traffic areas.

Fig 6. Synthetic Vision Primary Flight Display with Traffic Indicated

VII. Conclusion

Honeywell's IPFD, a synthetic vision application for fixed wing aircraft and helicopters, mimics and enhances critical features of the external environment under daylight visual conditions to support situational awareness during low-visibility or night-time conditions. In addition to serving as a situation awareness display, the role of the SV primary flight display will continue to evolve and grow. The present study provided strong pilot acceptance, usability and anticipated safety benefits of incorporation of EGPWS terrain and obstacle alerts into the SV display. Future SV EGPWS display research should investigate requirements for or against terrain and obstacle alert recovery symbology (e.g., similar to TCAS fly-to or fly-away zones during a resolution advisory), adequacy of display during GPWS radar altimeter based alerts, and display requirements for EGPWS alerts outside default field of view of the SV PFD displays.

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Impact of the Communication Ranges in an Autonomous Distributed Task Allocation Process within a multi-UAV Team Providing Services to SWIM Applications

Ivan Maza, Anibal Ollero, and David Scarlatti

***Abstract*— Taking into account the required scalability of SWIM and the emerging UAV technologies, it is expected to have UAVs supporting SWIM applications and even new UAV based applications. For instance, it could be possible to have a team of UAV acting as weather sensors improving the performance of a SWIM weather application. In this context, and due to the autonomous nature of the UAVs, it is possible to embed autonomous decision-making tools in the software on-board the UAVs for providing services in the SWIM architecture. Furthermore, to increase the robustness of the system w.r.t. the communication infrastructure limitations, distributed autonomous decision tools are considered instead of centralized decision-making. An important issue in distributed multi-UAV coordination is the *distributed task allocation* problem that has recently become a key research topic. Our approach to the distributed task allocation problem considers the application of market-based negotiation rules. Based on this method, the UAVs themselves will autonomously decide which one will be endowed with each task. In the missions considered in the paper, a team of UAVs has to provide services to a SWIM application. Those services have been modeled by tasks consisting in visiting waypoints transmitting data in real time. The distributed execution of the algorithm applied in the paper will compute which UAV will visit each waypoint during the mission. Moreover, the algorithm will also create and allocate communication relay tasks if the limited communication range does not allow to send the data in real-time. The paper shows the result of several simulations considering different communication ranges.**

***Index Terms* — Distributed decision-making, SWIM architecture, Unmanned aerial vehicles**

I. Introduction and Motivation

It is known that current Air Traffic Management (ATM) Systems are based on rigidly configured systems connected by hardware to geographically dispersed facilities. Then, they are expensive, and their modifications are very costly and time consuming.

Future capacity demands require the implementation of new network-enabled operational capabilities that are not feasible within the current ATM systems. In fact, the safety, capacity, efficiency and security requirements to meet this expected demand require the application of new flexible ATM architectures. A new approach to face this future demand is the so-called System Wide Information Management (SWIM). This system enables shared information across existing, disparate systems for network-enabled operations, and improves air traffic operations by integrating systems for optimal performance. Boeing's preferred solution to the Next Generation Air Transportation System, SWIM [1], is seen as well as a global solution for the future SES (Single European Sky) and worldwide ATM systems.

On the other hand, the commercial application of Unmanned Aerial Vehicles (UAVs) requires the integration of these vehicles in the ATM. A relevant feature that arises from the integration of the UAVs is the potential improvement that can be achieved in several layers of the SWIM architecture. For example, in the application layer, the service provided by the weather application could be improved by an UAV acquiring information from areas with high uncertainty in the weather conditions (see Section II). A more significant improvement could be achieved when considering several cooperating UAVs. In this context, and due to the autonomous nature of the UAVs, it is possible to embed autonomous decision-making tools in the software on-board the UAVs for providing services in the SWIM architecture. Furthermore, to increase the robustness of the system, distributed autonomous decision tools are considered instead of centralized decision-making. An important issue in distributed multi-UAV coordination is the *distributed task allocation* problem that has recently become a key research topic. It deals with the way to distribute tasks among the UAVs and requires to define some metrics to assess the relevance of assigning a given task to each UAV.

Within the distributed approaches, the market-based approach [2] has been the most successful one and is based on the *Contract Net Protocol* ([6], [7]). In this paper, an algorithm following that approach have been simulated in the

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context of multi-UAV missions providing services to a SWIM application. Those services have been modelled by tasks consisting in visiting waypoints transmitting data in real time. The distributed execution of the algorithm applied in the paper will compute which UAV will visit each waypoint during the mission. Moreover, the algorithm will also create and allocate communication relay tasks if the limited communication range does not allow to send the data in real-time. The paper shows the result of several simulations considering different communication ranges.

In the next section, an example of a SWIM application that could be improved through the use of a team of UAVs is presented. This application provides the context in which a distributed decision-making algorithm described in Section IV has been tested. The description of the mission to be executed by the team of UAVs and the simulation results are presented in Sections III and V respectively. Finally, some conclusions are listed in Section VI.

II. UAVs improving the performance of a SWIM weather application

Taking into account the required scalability of SWIM and the emerging UAV technologies, it is expected to have UAVs supporting SWIM applications and even new UAV based applications. One example could be the use of UAVs as weather sensors reporting real-time information flying at a given altitude from areas with high uncertainty in the weather estimation.

Having in mind the SWIM architecture proposed in [3], the weather servers could compute a list of waypoints to be visited for gathering weather data. Those servers would have access to the future air traffic requesting this information to their corresponding brokers. Therefore, the waypoints could be prioritized depending on the expected routes in a given area.

The waypoints list will be sent to a team of UAVs that could autonomously allocate the waypoints among themselves using distributed algorithms trying to optimize some criteria, such as minimizing the total mission time.

Figures 1 and 2 show how the UAVs, acting as weather data sources, fit well in the proposed SWIM architecture [3]. In these figures, four stages in the information flow have been identified by different connecting lines labeled with numbers from 1 to 4. In the first phase (Fig. 1), composed by two stages (connecting lines labeled as 1 and 2), the UAV receives (via an ATM broker) a request consisting in a “goto” command. The UAV executes it and go to the specified location to gather weather information with the sensors on-board. In the second phase (Fig. 2), the UAV reports weather data to the closest SWIM weather broker and then send the information to the weather repository (connecting lines labeled as 3 and 4).

This application provides the context in which a distributed decision-making algorithms for the UAVs have been tested. The mission to be executed by the team is described in next section.

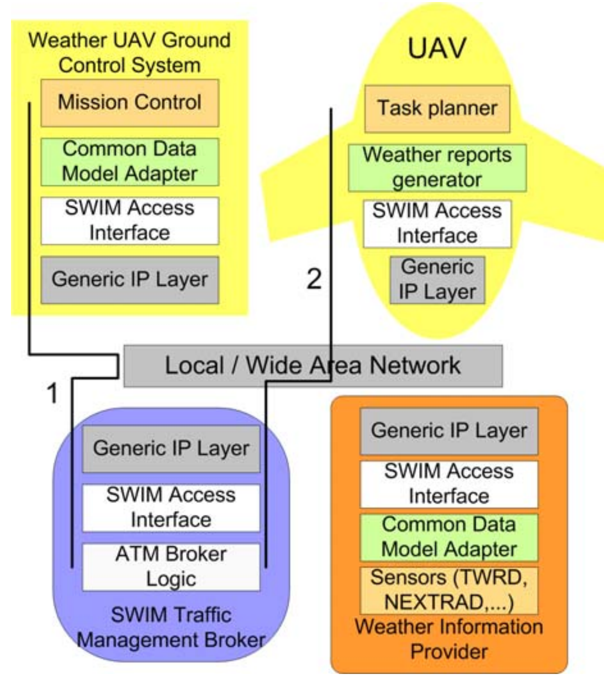

Fig. 1. UAV acting as a weather sensor. In a first phase, the UAV receives a request consisting in a “goto” command from an ATM broker.

III. UAVs mission description in a weather application context

The mission to be executed by the UAVs consists in reporting weather data in real-time to the closest SWIM weather broker from several areas. Therefore, each area should be visited by an UAV and its closest SWIM weather broker has to be within its communication range in order to receive weather data in real-time. But if it is beyond the communication range, another UAV has to provide a communication relay service to the UAV reporting weather information.

Therefore, the mission is composed by:

- Tasks: reporting weather data in real-time from a given area.
- Services: acting as a communication relay.

Regarding the communication relay services, it should be noted that can be allocated recursively, i.e., an UAV that executes a service could also need another service to accomplish the first one and in this way to any number of recursive services. In order to illustrate this characteristic, Figure 3 shows a situation in which the transmission to the SWIM broker requires two UAVs acting as communication relay.

IV. Cooperative distributed task allocation method

The algorithm applied to solve the missions described in the previous section is called S+T [8]. This protocol is based on a distributed market-based approach and integrates the concept of services: an UAV can ask to others for communication relay services in our case when it cannot send the weather data directly to the SWIM broker. The cost of the weather task used in the auctions during the negotiation protocol would be the sum of the cost of the task plus the cost of the service (or services) required.

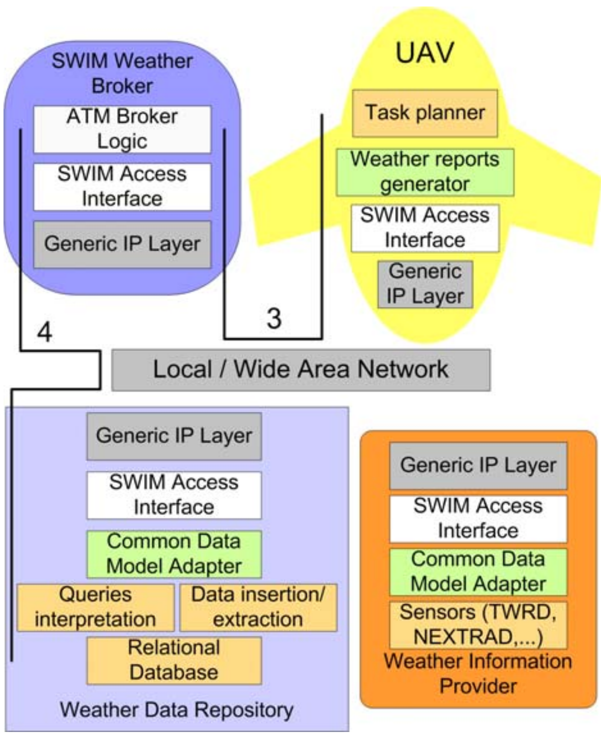

Fig. 2. UAV acting as a weather sensor. In a second phase, the UAV reports weather data to the closest SWIM weather broker and then send the information to the weather repository. It is possible to insert this service in the future Single European Sky (SES) as a SWIM enabled component.

The use of services increments the cooperation among UAVs and allows to achieve missions that could be impossible using a regular task allocation algorithm. However, services also increment the total time of the mission since more than one UAV are used to execute one task and, therefore, less tasks can be executed in parallel. In the S+T algorithm, the priority between the total time of the mission and its global cost can be adjusted with a parameter called α and defined as follows:

$$\alpha = \frac{P}{1-P} \tag{1}$$

where $P \in [0,1]$ is the priority to optimize the total time of the mission. This parameter is used in the calculation of the cost for the service.

$$C_s = C_o \cdot (1 + \alpha \cdot L) \tag{2}$$

where C_o is the original cost of the service, C_s is the new cost of the service and L is the level of the service, i.e., if it is the first service that depends on a task, L is equal to 1. If it is a service that depends on the first service, then L is equal to 2 and so on. This second parameter is used in order to penalize the use of more than one UAV to execute one task and when the use of services is unavoidable to increase the priority of services that need less UAVs.

The value of the priority P should be selected depending on the type of mission. If it is more important to optimize the global cost (in terms of energy) of the mission and the total time is not important for us, we should select $P = 0$, which means $\alpha = 0$. On the other hand, if we want to optimize the total time of the mission without considering the complete success of all the tasks, we should select $P = 1$ which means $\alpha \to \infty$ (no services considered).

V. Simulation Results

A C++ multi-UAV simulator has been developed to test decentralized algorithms. This simulator is based on an architecture designed for heterogeneous robots and divided into three layers [4]. The communication among UAVs is based on IP using BBCS [5], so it can also be used as an interprocess communication method for simulations. The other two layers are used to execute the different tasks allocated to the UAV and make easier the creation of new algorithms by using a modular and component-based architecture.

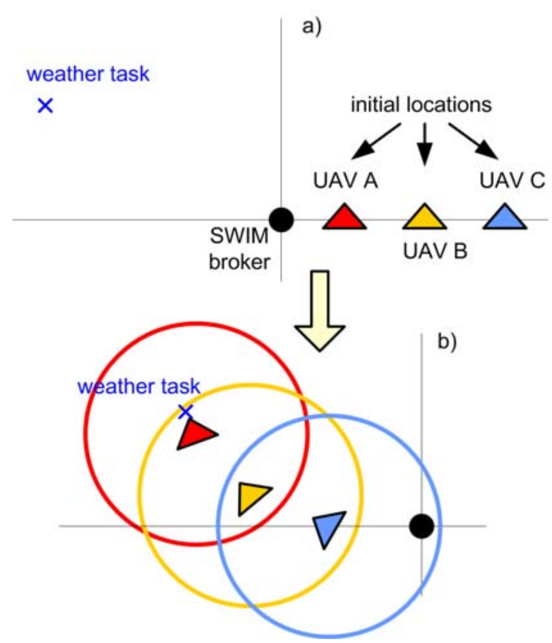

Fig. 3. Example of multiple recursive services required to accomplish one task. The left part shows the initial positions of the UAVs and the SWIM

broker. The right part shows the final assignment of tasks and services that allows UAV A to transmit images to the broker using UAVs B and C as communication relays.

In the simulations, weather reporting missions where UAVs have to send back data to the SWIM brokers from a certain area were considered. Therefore, an UAV transmitting weather data has to be within the communication range of the broker using its own communication device or using one or more UAVs as communication relays (services).

For this particular scenario, the execution synchronization between tasks and services has been implemented using preconditions, i.e., a task cannot start until all the services associated to it has been executed. Also, the UAV or UAVs that execute a service cannot start the next task or service in their local plan until the task associated to it has been finished.

In Fig. 4, the global cost (sum of the distances traveled by each UAV) decreases when the communication range increases as far as the probability to require a communication relay service decreases. Moreover, the mean of the global cost decreases when the number of UAVs increases due to the fact that a constant number of tasks is used in all the missions.

Numerous simulations with different number of UAVs were performed for the weather missions mentioned above with several communication range values. The resulting mean values of some parameters are shown in Table I. It shows that the number of services executed increases when the communication range of the UAVs decreases and, as a logical consequence, the number of messages received by one UAV and the global distance traveled by all of them also increases, as it was mentioned above. This means that the communication requirements and the energy needed to execute the mission will be bigger when the number of services increases.

On the other hand, simulations have been run with different values of the α parameter that depends on $P \in [0,1]$ (see Section IV). As can be seen in Fig. 5, one hundred random simulations have been executed for different values of P .

$P = 0$ is an extreme case that is used when it is wanted to minimize the global cost of the mission in terms of energy, and therefore, the cost of the services is not modified. Also in Fig. 5, it can be observed how the maximum distance traveled by one UAV decreases when P increases, and therefore, the time of the mission will be smaller (assuming the same speed for all the UAVs) because of the penalization of the costs associated to the communication relay services. For all the values shown in Fig. 5, all the tasks of the missions are completed.

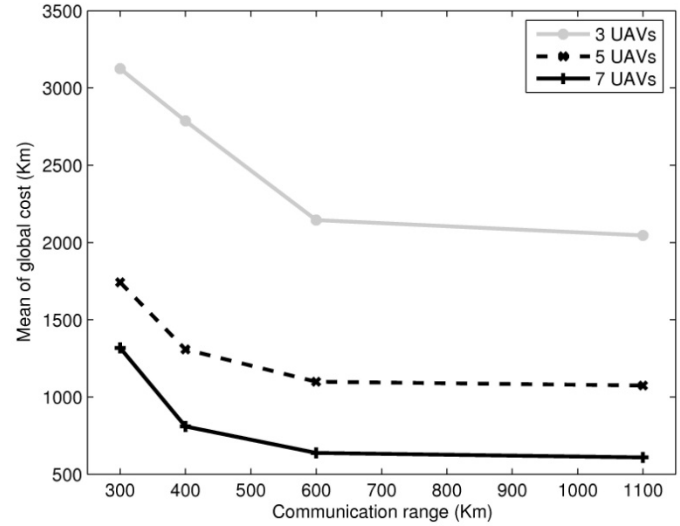

Fig. 4. Mean of the global cost over one hundred missions with different communication ranges, number of UAVs and five tasks.

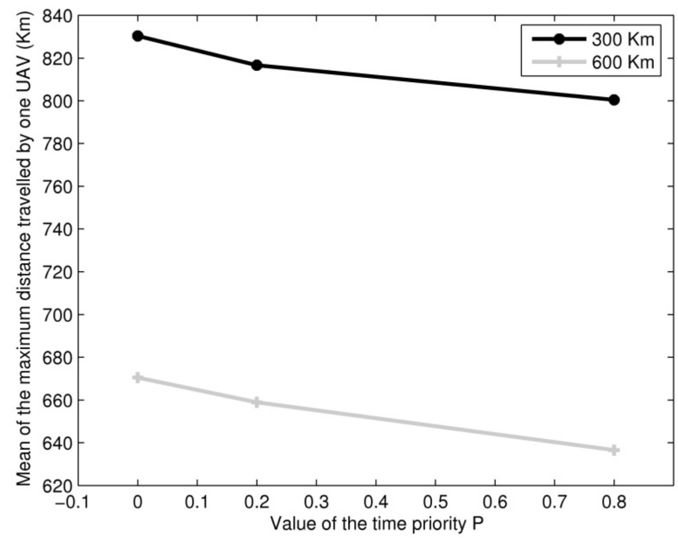

Fig. 5. Mean of the maximum distance traveled by one UAV over one hundred missions with 300 Km and 600 Km as communication ranges and five UAVs and tasks.

However, if the execution time is critical, with $P = 1.0$ the S+T algorithm services are not considered and some weather tasks could be undone (mission partially accomplished).

In Fig. 6, it is shown the mean of the number of tasks executed over 100 missions with different values for the communication range and with $P = 1.0$. Up to six hundreds kilometers, it can be seen that a significant number of tasks cannot be accomplished for the group of UAVs if the use of services is not considered. Therefore, we have to be careful when the parameter P is equal to 1.0 and a given mission needs services to execute most of the tasks. In that case, the time of the mission will be minimized but many tasks will not be executed. Then, it is advisable to use $P = 1.0$ only when most of the tasks can be executed without services and the execution time for the mission is very critical.

VI. Conclusions

Taking into account the required scalability of SWIM and the emerging UAV technologies, it is expected to have UAVs supporting SWIM applications and even new UAV based applications. In this paper, a SWIM weather application using a team of UAVs acting as weather sensors has been presented as an example. Due to the autonomous nature of the UAVs, embedded autonomous decision-making tools in the software on-board the UAVs for providing services in the SWIM architecture have been considered.

A distributed autonomous task allocation algorithm called S+T has been applied in several simulations of weather missions in which the UAVs had to report weather information in real-time from several areas to their closest SWIM broker. If the communication range does not allow a direct link, the algorithm implemented creates and allocates the required communication relay services.

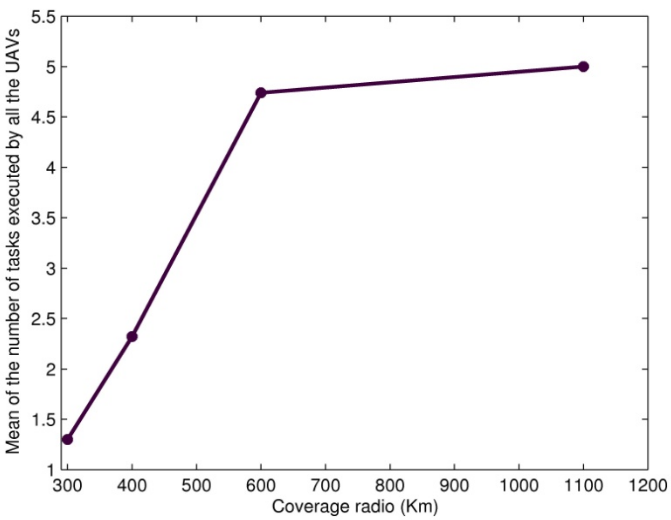

Fig. 6. Mean of the number of tasks executed by all the UAVs over one hundred missions with different values of the communication range and five UAVs and tasks. The use of services is not considered in this simulations, i.e., $P = 1.0$ or $\alpha \rightarrow \infty$.

The simulation results show how the autonomous computing capabilities of the UAVs can be used to improve the performance of the future SWIM applications even without a centralized planner process. Furthermore, the SWIM architecture allows the implementation of protocols such as the S+T used in this paper, pointing out the interest of that architecture in future ATM systems.

Acknowledgment

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Wake Vortex Monitoring & Profiling by Doppler X-band Radar in all Weather Conditions

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Abstract— **In order to improve the capacity of airports in view of the expected increasing amount of traffic the knowledge about the safety issues caused by wake vortices has to be improved. The final goal is to build up a wake vortex alert system to ensure the application of appropriate but not over-sized safety distances in all weather conditions. Lidar systems are able to deliver very accurate data, but are also sensitive to rain and fog. THALES did trials with the X-band radar BOR-A 550 on Orly Airport in November 2006 at Initial Take-Off and in September 2007 at ILS Interception Area. Operational continuous Detection, characterization (strength: circulation) and profiling (age: young/mature/old /decaying) capabilities of wake vortices up to a range of 1500 m have been proved in clear air and rainy weather. Opportunity detection of wake vortex was also obtained at long range until 7 Km in clear air. The Doppler resolution of around 0.2 m/s used with regularized high Doppler resolution techniques is able to characterize the wake vortex speed distribution in detail. X-band Radar is a full-fledged alternative, which can make a significant contribution to a wake vortex alert system.**

Index Terms— **Wake Vortex Hazard Mitigation, Wake Vortex Advisory System, Airport Safety & Capacity, High Resolution Doppler Analysis, Wake Turbulence Monitoring, X-band Radar.**

I. Introduction

WITH the steady increase in air traffic, civil aviation authorities are under continuous pressure to increase aircraft handling capacity. One potential approach is to reduce the separation distance between aircraft at take-off and landing without compromising safety. ICAO safety provision for aircraft separation criteria has been defined in the early 70's and has, since then, served to maintain acceptable standards of wake vortex safety. Such standard is based on fixed distance or time separation between aircraft according to their respective category, without indexing according to weather conditions (cross-wind, eddy dissipation). These ICAO Standard Safety separations are very conservative.

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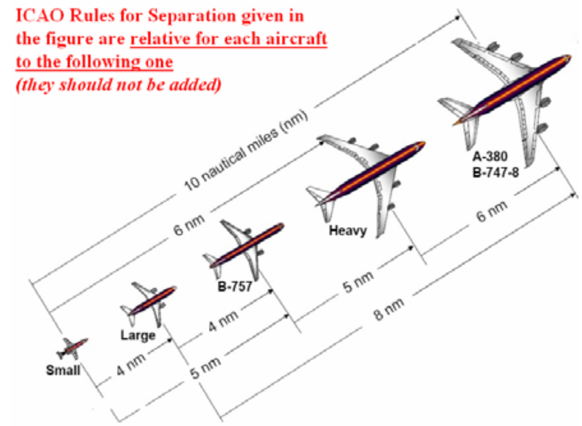


Fig. 1 : ICAO Standard Separation (in Nautical Miles)

Wake vortices are a natural by-product of lift generated by aircraft and can be considered (or viewed) as two horizontal tornados trailing after the aircraft. A trailing aircraft exposed to the wake vortex turbulence of a lead aircraft can experience an induced roll moment (bank angle) that is not easily corrected by the pilot or the autopilot.

However these distances can be safely reduced with the aid of smart planning techniques of future Wake Vortex Advisory Systems based on Wake Vortex detection/monitoring and Wake Vortex Prediction (mainly transport estimation by cross-wind), significantly increasing airport capacity. This limiting factor will be significantly accentuated soon with the arrival of new heavy aircrafts: Airbus A380 and the new heavy version of Boeing B747-8 (For A380, ICAO has recommended new safety separation larger than those already applied for B747 and UK authorities have announced in November 2006, the introduction of "Super Wake Vortex Category" for Airbus A380 with additional constraint).

Aircraft creates wake vortices when flying. The concern is even worst during taking off and landing phases, as aircraft are less easy to maneuver. To avoid jeopardizing flight safety by wake vortices encounters, time/distance separations have been conservatively increased, thus restricting runway capacity. These vortices usually dissipate quickly (decay due to air turbulence or transport by cross-wind), but most airports operate for the safest scenario, which means the interval between aircraft taking off or landing often amounts to several minutes. However, with the aid of accurate wind data and precise measurements of Wake Vortex, more efficient intervals can be set, particularly when weather conditions are stable. Depending on traffic volume, these adjustments can generate capacity gains (see European ATC-Wake results [8][9]), which have major commercial benefits.

Main objective is to develop a Ground/Board Collaborative Wake Vortex Advisory System that would allow variable aircraft separation distances, as opposed to the fixed distances presently applied at airports. This Wake Vortex Advisory System should integrate wake vortex detection/monitoring sensors used in decision-support system and procedures that will help air traffic controllers decide how long the intervals should be.

Candidate sensors are based on ground low cost Lidar & Radar technologies (1.5 µm VLS14 Pulsed Lidar from LEOSPHERE & ONERA and X-band Doppler Radar BOR-A550 from THALES). These sensors could be used to continually monitor Wake turbulence on runways or at ILS Interception area. Wake turbulence data is combined with meteorological data & Wake Vortex Predictor [3] to generate recommendations for intervals, which are displayed on the air traffic controller's screen. Currently, Lidar sensors are used for wake vortex measurements, but their performance could be limited in adverse weather like rain or fog. On the other hand, Radar is a good complementary sensor, which can be used for turbulence remote sensing as well (wake vortex, wind-shear, micro-bursts). It is able to work in different weather conditions like fog, rain, wind, and dry air. Up to now, there was a lot of research on wake vortex detection with Radar on different frequency bands [5]. To collect data on different weather conditions, the X-band Radar BOR-A 550 was deployed near to a runway of ORLY airport and just under ILS Interception Area (entering of the glide path). In these scenarios Radar measurements on different weather conditions were performed.

BOR-A550 has been awarded by the "Frost & Sullivan 2006 Market leadership Award" in recognition of its achievement (150 BOR-A are under contract over the world).

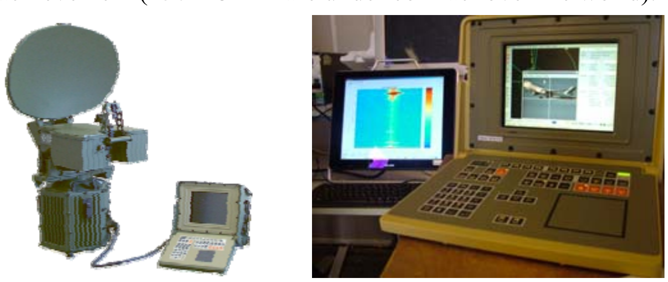


Fig. 2 : X-band Doppler BOR-A550 Radar & its HMI

Fig. 3 : Paris Orly Airport Radar Trials (horizontal scanning of runways)

Fig. 4 : Limours Radar Trials (vertical scanning of ILS Interception Volume)

II. WAKE VORTEX HAZARD

In this section, we will describe physics of Wake Vortex hazard and the origin of Wake Vortex radar cross section in clear air. These elements are important to analyze Doppler Radar measurements.

A. *Physics of Wake Vortex Hazard*

The Wake Vortices shed by an aircraft are a natural consequence of its lift. The wake flow behind an aircraft can be described by near field and far field characteristics. In the near field small vortices emerge from that vortex sheet at the wing tips and at the edges of the landing flaps.

After roll-up the wake generally consists of two coherent counter-rotating swirling flows, like horizontal tornadoes, of about equal strength: the aircraft wake vortices.

When the forces which act on the aircraft are in balance, the aircraft lift and the flux of wake vertical momentum are also equal to the weight of the aircraft. We can then observe that Wake Vortex Circulation Strength (root circulation in m2/s) is proportional to Aircraft mass and inversely proportional to Wingspan & Aircraft speed:

$$\Gamma_0 = \frac{M.g}{(\rho.V.s.B)} \quad \begin{cases} M\text{: Aircraft mass} \\ V\text{: Aircraft Speed} \\ B\text{: Wingspan} \end{cases} \quad \begin{cases} g\text{: Gravitational} \\ \quad \text{acceleration} \\ \rho\text{: Air density} \\ \Gamma_0\text{:Root Circulation} \\ s = \pi/4 \end{cases} \qquad (1)$$

For a single and axi-symmetric vortex the circulation is given by:

$$\Gamma(r) = 2\pi.r.v_\theta(r) \qquad (2)$$

Other characteristics of wake vortices are the following:

- Initial vortex spacing (m) : $b_0 = s.B$ with $s = \dfrac{\pi}{4}$
- The two counter rotating vortices rolling off the wing tips create a downwash velocity that pulls the wake vortex pair down after leaving the aircraft. Descent speed of vortex pairs (m/s): $\dfrac{\Gamma_0}{2\pi.b_0}$ (3)

One way of characterizing vortex is by its velocity profile:

$$v_\theta(r) = \frac{\Gamma_0}{2\pi r}\left(1 - e^{-f\left(\frac{r}{B}\right)}\right) \qquad (4)$$

In the following figure, radial profiles of the tangential velocity that is frequently used to model a vortex in the rolled-up wake behind an aircraft is given. Time Velocity Profiles evolution is illustrated:

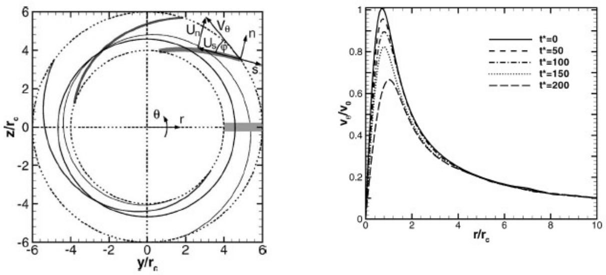


Fig. 5 : Tangential Velocity Profiles at different instants in Time. Velocity Profiles are averaged over radial and azimuth directions

Additional factors that induced specific dynamic of wake vortices are:

- Wind Shear Effect (stratification of wind)
- Ground Effect (rebound)
- Transport by Cross-wind

Fig. 6 : Wake Vortex Dynamic (real picture)

Fig. 7 : Ground Effect on Wake Vortex

The next value, we need to know is the characteristic time scale for the wake vortex to decay. The two counter rotating vortices rolling off the wing tips create a downwash velocity that pulls the wake vortex pair down after leaving the aircraft. A characteristic time scale can be defined as the time it takes for the vortex pairs to descend one wing span (t').

Time taken for the vortex pairs to descend one wing span:

$$t' = 0.38.\frac{B^3.V}{M} \quad (5)$$

If the ambient background turbulence eddy dissipation rate ε is measured to be above a threshold value, $\varepsilon \geq 10^{-4} m^2/s^2$, the crow instability is empirically observed to lead to a coherent circulation decay rate.

Fig. 8 : Coherent Circulation Wake Vortex decay by Crow Instability

Once this background threshold is exceeded, the accelerated wake vortex circulation decay rate can be bound by the empirical observed equation and is predicted to be bellow naturally occurring atmospheric turbulent levels near the ground in 8 to 9 non-dimensional time periods :

$$\Gamma = \Gamma_0\left(1 - \frac{t^*}{8}\right) \quad with \quad t^* = \frac{t}{t'} \quad (6)$$

It is reasonable for a conservative safe separation distance to be determined by the time it takes for the preceding aircraft's wake to decay to an observed typical atmospheric boundary layer background circulation level of $\Gamma_{bg} = 70\,\mathrm{m}^2/s$. Then, we obtain by using preceding equations:

$$t_{\Gamma_{bg}} = 8.t'\left(1 - \frac{\Gamma_{bg}}{\Gamma_0}\right) \quad (7)$$

B. Wake Vortex Radar Cross Section in Clear Air

During 80's & 90's different Radar trials have been made in UK, France & US for wake vortex monitoring in clear Air with positive results for different bands (VHF/UHF/L/S/C/X bands) at short range (few kilometers). US radar campaigns are detailed by Gilson [27] and in K. Shariff & A Wray [5].

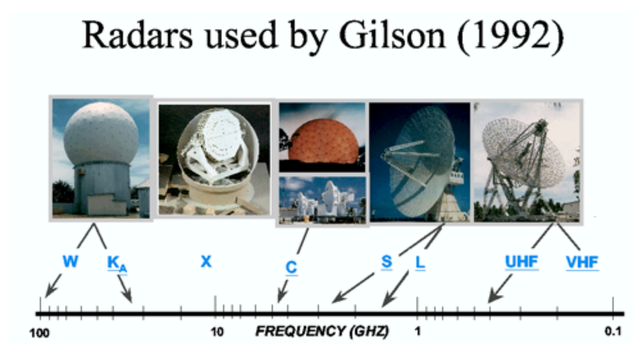


Figure 9 : radars used for Wake Vortex Campaign in Gilson Campaign (1992)

In Europe, joint radar trials have been made:

- ***Sheppard (1992)***[34]: detection at Range R = 2.8 Km with an S-band Radar (3 GHz) (DX 04 Radar Campaign by GEC-MARCONI)

- ***Bertin (1992)***[35][36]: detection at Range R = 0.5 Km with an UHF-band Radar (961 MHz) (PROUST Radar campaign by CNRS/CRPE)

In Gilson [27][5], it was observed that Wake Vortex RCS was relatively flat as a function of frequency. Particulates were not involved (they would give f^4 Rayleigh scattering). The frequency dependence was not the Kolmogorov $f^{1/3}$. Furthermore, the RCS measurement 1 Km behind the plane was insensitive to engine thrust and flat setting.

In [27][5], tests have revealed radar echoes from aircraft wakes in clear air. The mechanism causing refractive index gradients in these tests is thought to be the same as that for homogeneous and isotropic atmospheric turbulence in the Kolmogorov inertial range, for which there is a scattering analysis due to Tatarski: in a turbulent velocity field the presence of mean vertical gradients of potential temperature and humidity lead to fluctuations in refractive index (the radar cross-section per unit volume of isotropic turbulence in the inertial range is $\eta = 0.38.C_n^2.\lambda^{-1/3}$). Mechanism does not depend on atmospheric conditions (humidity has a weak influence) and Engine Exhaust has no role.

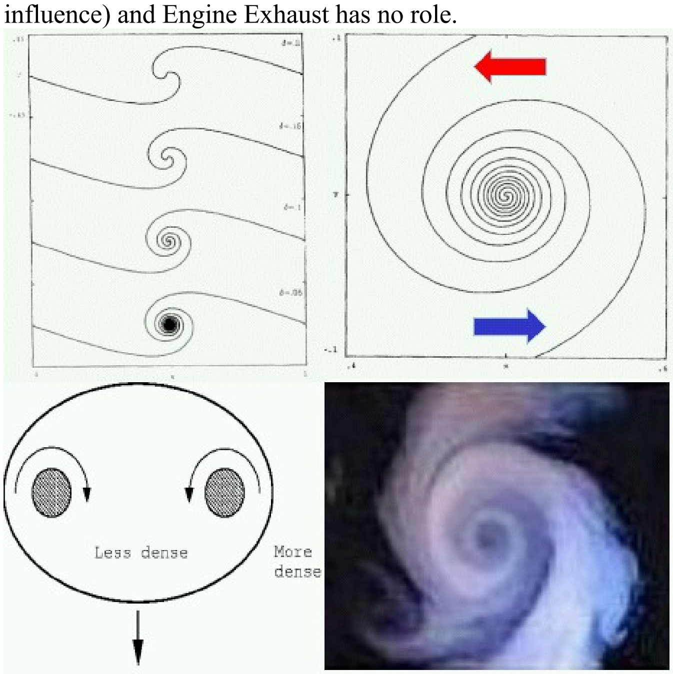


Fig. 10 : Physical Mechanism causing Radar refractive index gradient

Two mechanisms causing refractive index gradients are considered in [5]:

- **Radial density gradient in the Vortex Cores:** The core of each vortex, which has a lower density and therefore lower index of refraction. Radial Pressure (and therefore density) gradient in a columnar vortex arising from the rotational flow. The RCS is due to a density gradient in a vortex arising from a balance of radial pressure gradient and centrifugal forces:

$$(n-1).10^6 = 77.6\left(\frac{P_a}{T}\right) + 64.8\left(\frac{P_v}{T}\right) + 3.776.10^5\left(\frac{P_v}{T^2}\right)$$

$$with \begin{cases} n : \text{refractive index of humid air for frequ. below } 20\ GHz \\ P_a : \text{the partial pressure (mb) of dry air} \\ P_v : \text{the partial pressure (mb) of water vapour} \\ T : \text{the temperature (K)}, \quad T_\infty = 288K \end{cases}$$

$$\frac{P(r)}{P_\infty} = \left(\frac{\rho(r)}{\rho_\infty}\right)^{\gamma} = \left(1-(\gamma-1)\int_r^\infty \frac{1}{r}\frac{V_\theta^2}{c_\infty^2}dr\right)^{\gamma/(\gamma-1)}$$

$$with \quad V_\theta = \frac{\Gamma}{2\pi.r}\begin{cases} (r^2/r_0^2) & for \quad r < r_0 \\ 1 & for \quad r \geq r_0 \end{cases}$$

$$with \begin{cases} \rho(r) : \text{density in each vortex} \\ \rho_\infty : \text{ambient density} \\ c_\infty : \text{the ambient speed of sound } (341\ m/s) \end{cases}$$

$$and \quad \frac{T(r)}{T_\infty} = \left(\frac{P(r)}{P_\infty}\right)\left(\frac{\rho(r)}{\rho_\infty}\right)^{-1}$$

- **Transport of atmospheric fluid in the oval surrounding the vortices:** The oval surrounding the vortex pair that transports atmospheric air from one altitude to another. As it descends, the fluid in the oval compresses adiabatically in response to increasing ambient pressure.

$$\left[\tilde{n}(z)-\bar{n}(z)\right]10^6 = 223\left[\tilde{\rho}(z)-\bar{\rho}(z)\right] + 76.7\left[\tilde{\rho}_v(z)-\bar{\rho}_v(z)\right] + 1.75.10^6\left[\frac{\tilde{\rho}_v(z)}{\tilde{T}(z)} - \frac{\bar{\rho}_v}{\bar{T}(z)}(z)\right]$$

$$'' = -\frac{\bar{\rho}(z)N^2}{g}\Delta z\left[223 + \frac{\overline{RH}(z)P_{sat}(T_z)}{\bar{P}(z)}\left(76.7 + \frac{3.49.10^6}{\bar{T}(z)}\right)\right]$$

$$with \begin{cases} N : \text{Brünt-Väisälä Frequency (stratification parameter)} \\ \text{at Sea Level} : N = 0.014s^{-1} \\ \text{(in Summer) } N = 0.02s^{-1}\text{-}0.03s^{-1} \text{ (in Winter)} \\ \Delta z : \text{Descend Altitude} \\ P = P_a + P_v \end{cases}$$

III. X-BAND RADAR TRIALS ON PARIS ORLY AIRPORT

In November 2006, BOR-A was deployed on Orly Paris Airport by permission of ADP (Aéroport de Paris) and DGAC/ DSNA near to runway 07. It was possible to monitor wake vortices caused by medium sized planes like Boeing 737 and Airbus A320. Since the trial was scheduled in November, a variety of different weather situations like dry air, fog, rain, and wind did occur.

Following Figures show the Radar location used for the trial. BOR-A 550 was located on the roof of a building about 500 m away from runway 07. During the trial the take-off area was monitored for wake vortex encounters. The data were recorded in staring mode as well as in scanning mode. At the end of the trial, the surveillance area was set to the area below the glide path for landing planes.

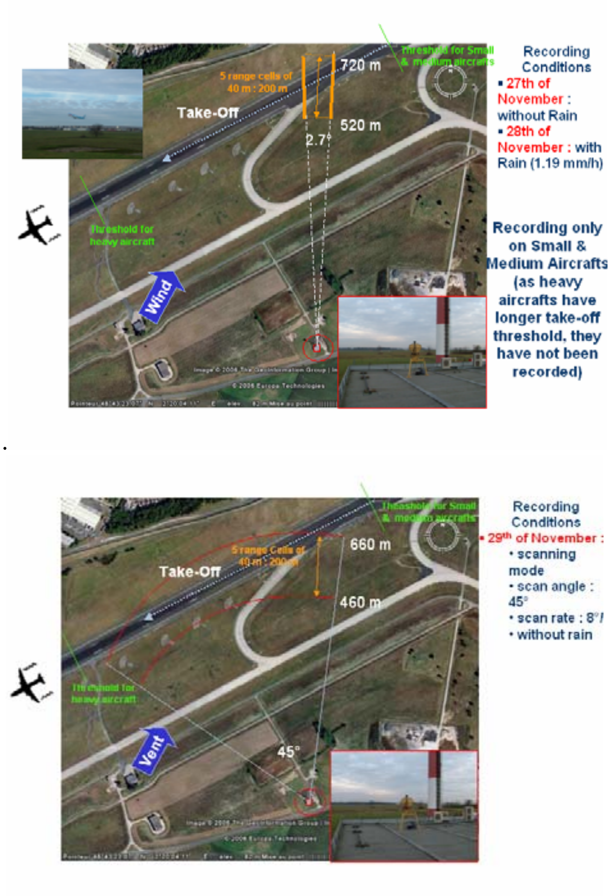


Fig. 11 : Staring (top) & scanning (bottom) modes

In order to correlate Radar Wake-Vortex Detection with wind conditions (head & cross-wind), 1.5 µm Pulsed Lidar Wind Profiler, WLS7 from LEOSPHERE (Spin-Off from Ecole Polytechnique), has been co-localized on same site to provide wind profiles from 0 to 160 m with 15 m range resolution and 0.1 m/s Doppler resolution, every second (average value, every minute).

Fig. 12. BOR6A550 Radar & LEOSPHERE Lidar Sensors at Paris ORLY Airport site

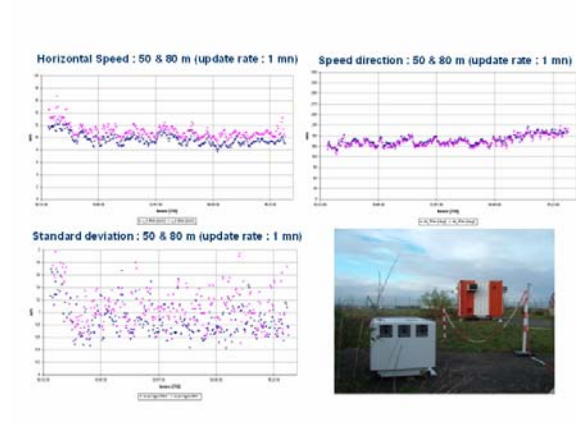


Fig. 13 : LEOSPHERE Lidar Wind Profiler data on 1 day

IV. X-BAND DOPPLER DATA ANALYSIS

The data-recording unit stores the complex Radar video signal with a range gate size of 40 m. This allows the recording of 5 range cells (200 m range swath) using a peak pulse power of 20 Watts (75 Watts in the new version). With the applied PRF, a Doppler velocity resolution of 0.2 m/s is achieved.

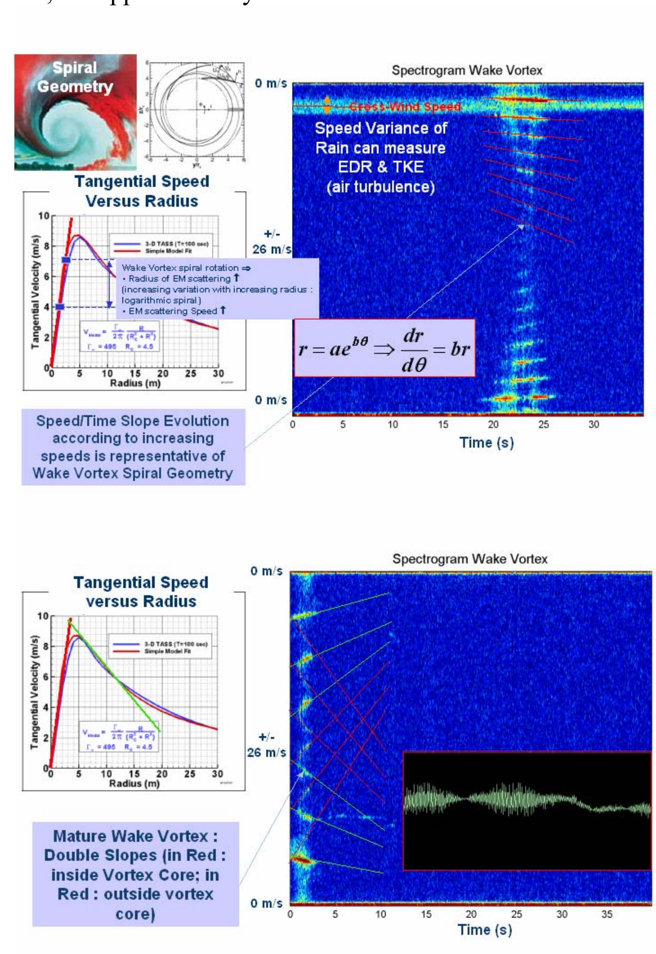


Fig. 14 : Time/Speed Slope Evolution representative of Wake Vortex (logarithmic) Spiral Geometry

We observe, on the Time/Doppler signature, slopes in Time/Doppler(speed) that can be interpreted by logarithmic spiral structure of wake vortex. Roll-ups are interlacing fences of air from surrounding and from higher altitude (adiabatic transport of fluid within vortex pair). When each roll-up rotates, range of reflecting points at each fence increase. According to Wake Vortex age and tangential speed law, this range evolution induced positive Time/Doppler slopes (young vortex), jointly positive/negative slopes (mature vortex), negative slopes (old & decaying vortices). In the following figure, spiral geometry of contra-rotating vortex roll-ups is illustrated. We can observe that roll-up curvature evolves with radius and time. For "young vortex", wake core is dense with high tangential speed increasing with radius. On the contrary for "old vortex", their cores have been destroyed by diffusion and tangential speed decrease with radius.

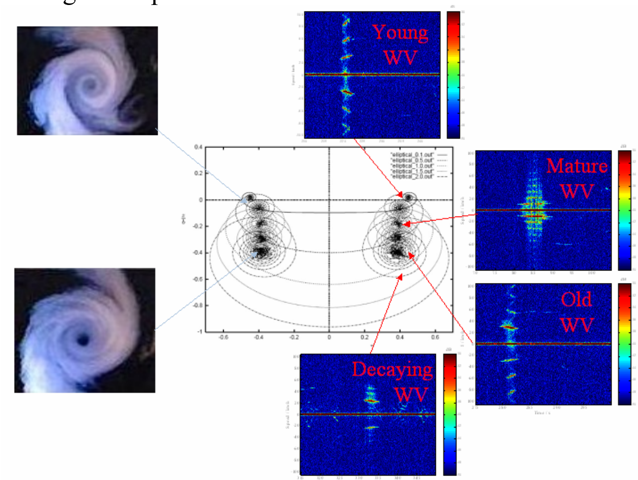


Fig. 15 : Evolution of Roll-up spiral geometry & Doppler spectrum (time/Doppler slopes) versus Age

In staring mode the direction of the antenna beam is fixed with a beam width of 2.7°. It was directed towards a point below the starting path after take-off. Following figure shows the Doppler signature of a young wake vortex. The sharp lines are indicators for the internal structure of spiral roll-up. The following figures are showing the next life stages.

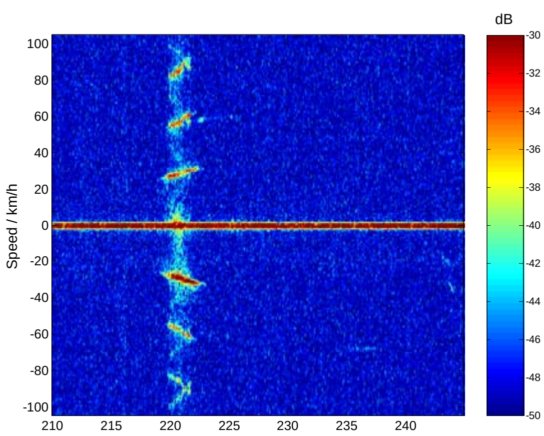


Fig. 16 : Time/Speed Slope Evolution representative of Wake in clear air

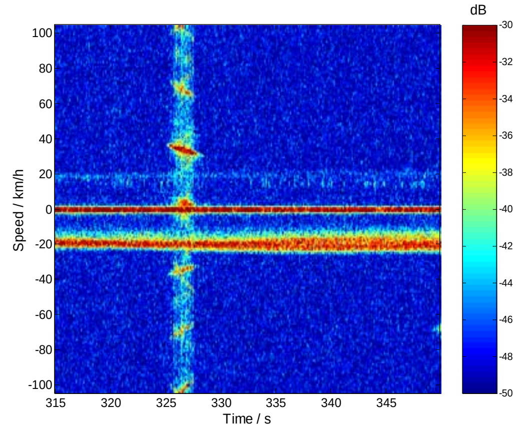


Fig. 17 : Time/Speed Slope Evolution representative of Wake in Rain

Following figure contains the Doppler signature of a mature wake vortex. The radial speed remains almost constant over time.

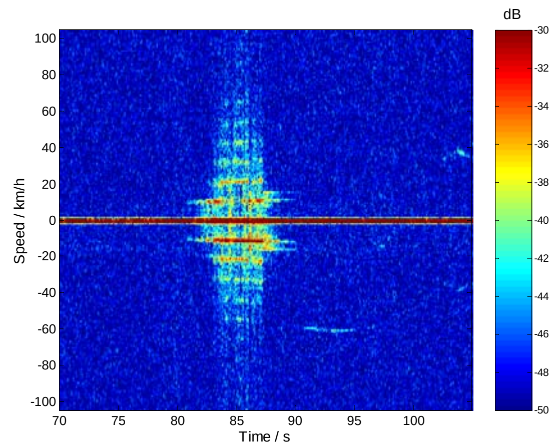


Fig. 18 : Doppler signature of a mature Wake Vortex

Moreover, the following figure shows a recording of a wake vortex, which has started to decay, and the following one presents the spectrogram of an almost decayed vortex.

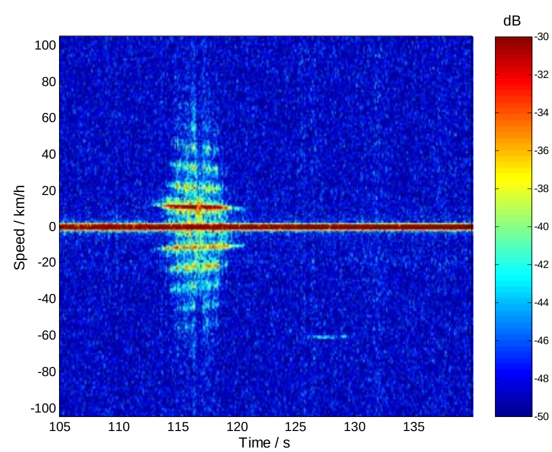


Fig. 19 : Doppler signature of a decaying Wake Vortex

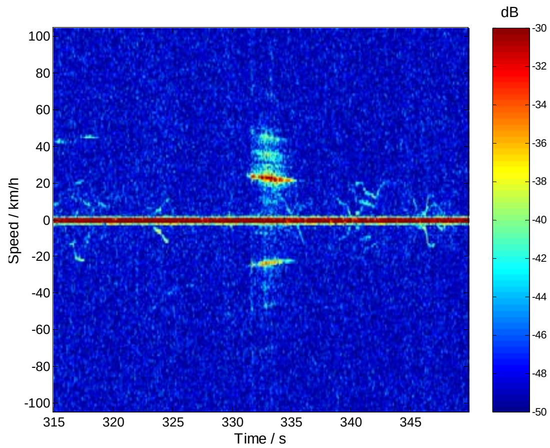


Fig. 20 : Doppler signature of a decayed Wake Vortex

In scanning mode the radar was continuously scanning a surveillance area of 45° with a speed of about 8°/s. In this area, wake vortices of medium sized (B737 & A320) planes have been all detected. For more heavy Aircrafts (A380 & B747-8), performances could be drastically improved. Due to the scanning process a number of sparse samples of the vortices are visible. Nevertheless, the speed components of the wake vortex can be tracked from scan to scan. Analysis of data obtained in scanning mode gives the same kind of information, than in staring, on the wake vortex geometry and age.

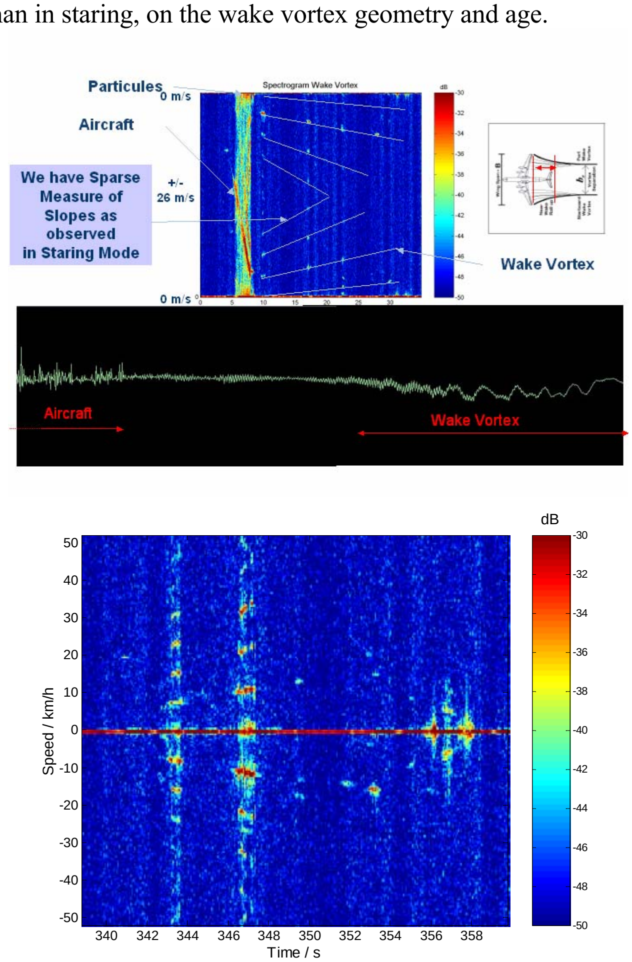


Fig. 21 : Doppler signature in scanning mode

The data recordings described above covered a range from 500 to 700 m. With the signal format used in this case a detection range up to 1000 m for wake vortex encounters can be assumed. At the end of the Orly trial the area beneath the glide path for landing planes was monitored in scan mode. In that case a longer pulse was used. Anecdotally, some very short wake vortex detections were also obtained at a distance of 7000 m using a sector width of 45°. In the following figure, the spectrogram of a sample of the recorded data is illustrated. It should be noted that in this case the landing path was in parallel to the radar beam, causing a receiving position that was clearly far from optimal. The distance and the angle caused a very low detection probability, but still some traces of wake vortex encounters could be found. Wake Vortex Detection range of 1/2 Km is compliant with operational request related to monitoring along the runway and glide slope.

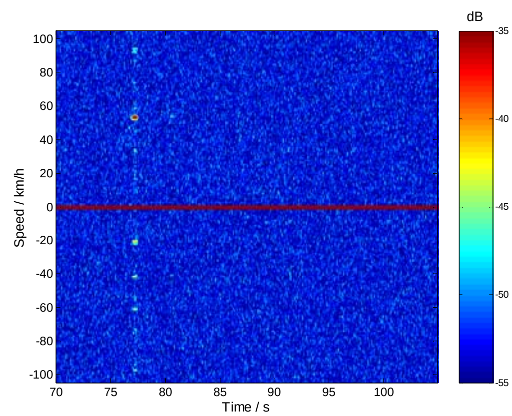


Fig. 22 : Wake Vortex Monitoring at 7 Km range

V. WAKE VORTEX MONITORING & PROFILING BASED ON HR RADAR DOPPLER PROCESSING

Based on recording of Doppler complex I&Q data, an advanced processing chain has been developed to:

- ***Detect Wake Vortex*** (in wet & dry conditions) at short range (<1.5 Km) in Scanning Mode (8°/s)
- ***Localize Wake Vortex*** in range/azimuth
- ***Characterize Wake Vortex:*** Geometry (Roll-up Spiral), Age & Strength (Circulation in m^2/s)

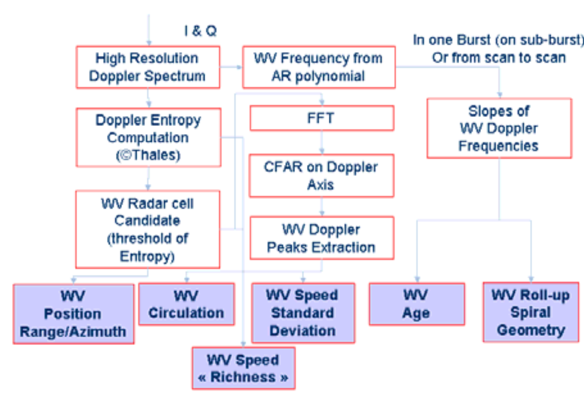


Fig. 23 : Doppler Radar Processing chain

Doppler Spectrum is coherent with theoretical model with a decreasing behaviour of Doppler Spectrum in $1/V^3$.

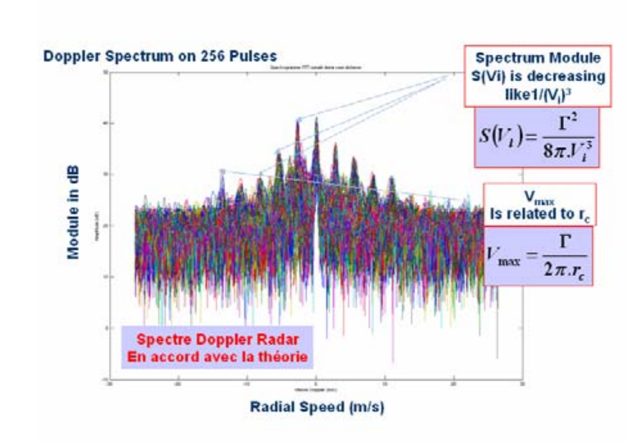


Fig. 24 : Wake Vortex Doppler Spectrum on successive time Bursts

Wake vortex detection is based on Regularized High Resolution Doppler analysis [12,13,14]. For this function, we have developed and tested a highly sensitive detector that estimate "richness of spectrum", that is based on High Resolution Doppler entropy assessment.

First, radar cell are localized by a threshold on Doppler entropy, that is defined by mean of information geometry [15]:

$$S=\sum_{k=2}^{n-1}(n-k)\left(\frac{1}{2}\ln\left(\frac{1+|\mu_k|}{1-|\mu_k|}\right)\right)^2 \quad (8)$$

with $\{\mu_k\}_{k=2,\ldots,n-1}$ reflection coefficient of complex regularized Autoregressive model.

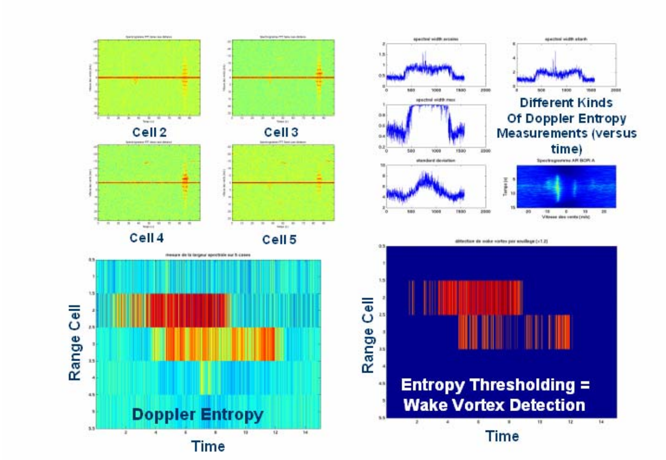


Fig. 25 : Wake Vortex Detection based on Doppler Entropy

Then, Wake Vortex strength is deduced [4] from circulation computed from $S(V_i)$ the spectral magnitude of a Doppler velocity bin, after previously applying CFAR on Doppler axis to extract Doppler peaks in spectrum :

$$\Gamma \propto \left[2\int_{V_{min}}^{V_{max}} V_i^2 [S(V_i)]^{2/3} dV_i\right] \Big/ \left[\int_{V_{min}}^{V_{max}} [S(V_i)]^{2/3} dV_i\right] \quad (9)$$

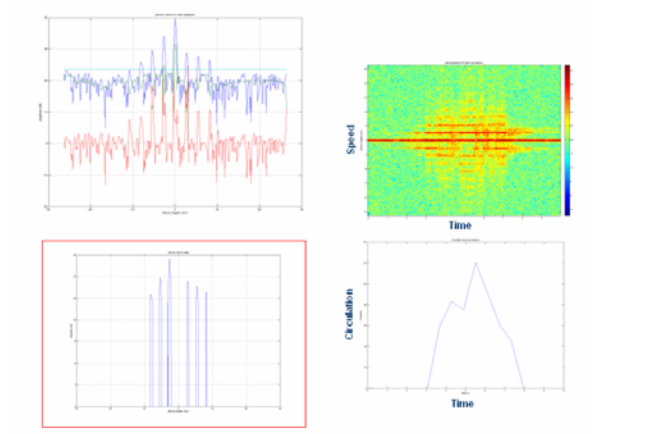
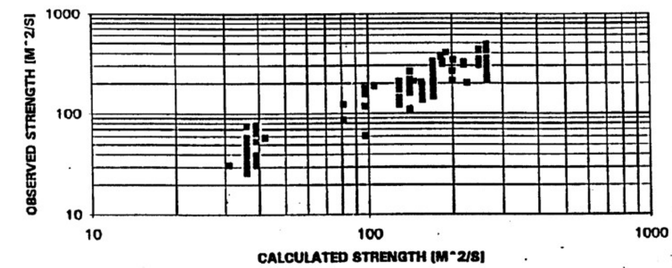


Fig. 26 : Circulation/strength estimation from Doppler spectrum

In case of RASS application, Rubin as successfully calibrated Wake vortex Circulation measurement by this kind of computation on Doppler Spectrum:



Comparison of Observed and Calculated Vortex Strengths

Fig. 27 : Validation of Doppler Radar Circulation Measurement by Rubin

Information on Wake vortex roll-up spiral geometry is given by $r=ae^{b\theta}\Rightarrow\frac{dr}{d\theta}=br$. We can deduce "b" parameter from Time/Doppler spectrum evolution:

$$\begin{cases} V(r)=\dfrac{\Gamma_0}{2\pi.r_c}\dfrac{r}{r_c} \\ r=ae^{b\theta}\end{cases} \Rightarrow b=\frac{1}{2\pi}\log\left(1+\frac{\delta_r V}{V}\right) \quad (10)$$

For this purpose, Doppler/Time slopes in Spectrum are automatically extracted by Radon/Hough transform :

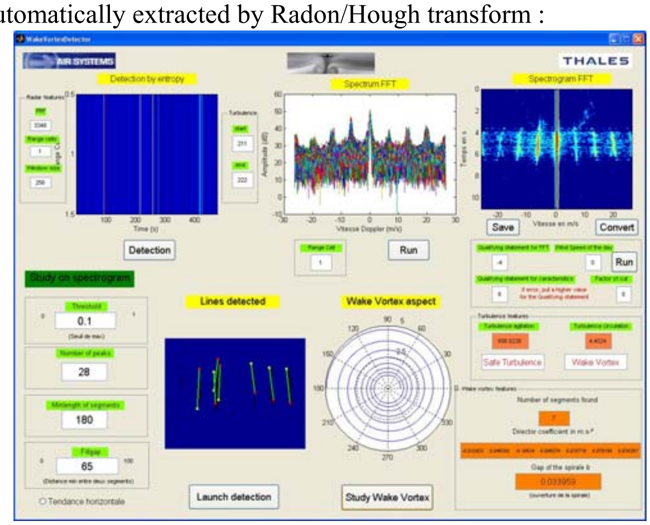


Fig. 28 : HMI for BOR-A data exploitation

In the following figure, risk of wake vortex encounters area are displayed in red in Radar Polar coordinate along runway :

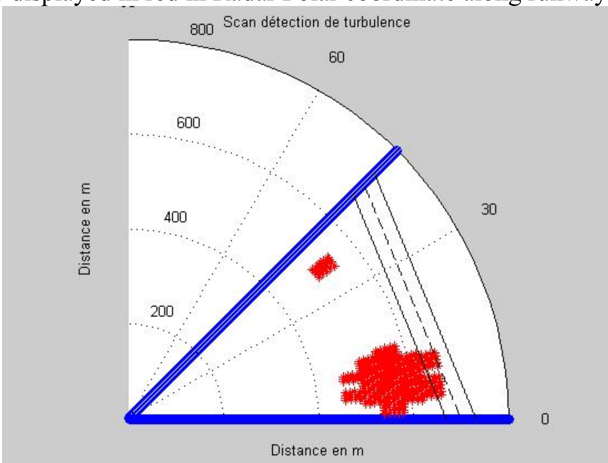


Fig. 29 : Wake Vortex Hazard Monitoring (Orly Runway)

VI. RADAR TRIALS IN ILS INTERCEPTION AREA

In October 2007, additional radar trials take place from THALES premises in Limours. This position has been used to monitor wake vortex in the glide slope of landing at ILS Interception Area. Airplane flied at around 1000 to 1500 m in altitude. The radar was installed on a test-bed tower.

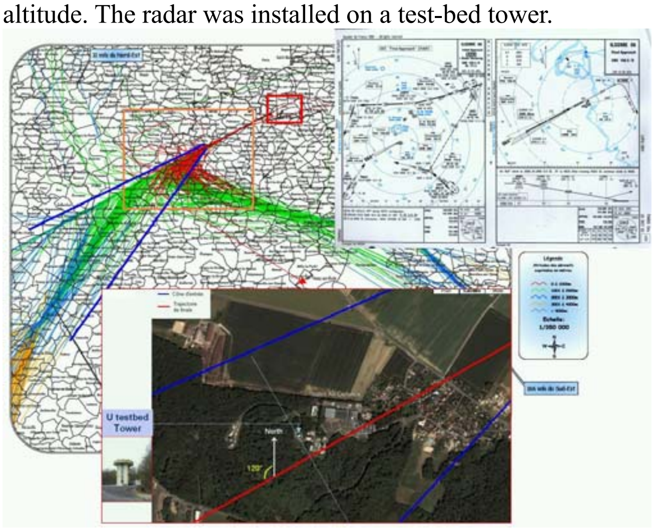


Fig. 30 : Limours trials & ILS glide slope position

Fig. 31 : Mechanical System developed for Zenithal Line of sight

A mechanical element has been built to embed the radar on positioning system of the test-bed tower, and to allow vertical scanning with zenithal line of sight.

For this trial, an upgrade version of BOR-A550 radar has been used with following specifications:

- Frequency: X Band
- Min/Max Range (resolution): 400 m / 40 Km (40 m)
- Beam Width (elevation/azimuth): 4°/2.7°
- Radial Velocity Range: +/- 26 m/s
- Doppler Resolution (& High Resolution): 0.2 m/s (0.04m/s)
- Mechanical Scan Rate: 8°/s
- Peak transmit power: 75 W

In the following figure, we have displayed Wake Vortex Doppler Entropy in Radar polar coordinate.

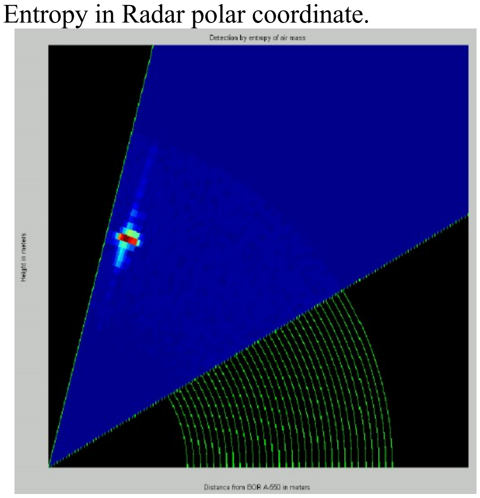


Fig. 32 : Wake Vortex Doppler Radar Entropy in polar coordinates

We have also designed a new interface to monitor and the profiling of wake vortex characteristics as Doppler spectrum, circulation, wake-vortex age and geometry. In scanning mode, we have to compensate Doppler modulation due to antenna rotation in order to assess exact Doppler/time slope of vortex roll-up. In the following figure, we illustrate new HMI for vertical scanning.

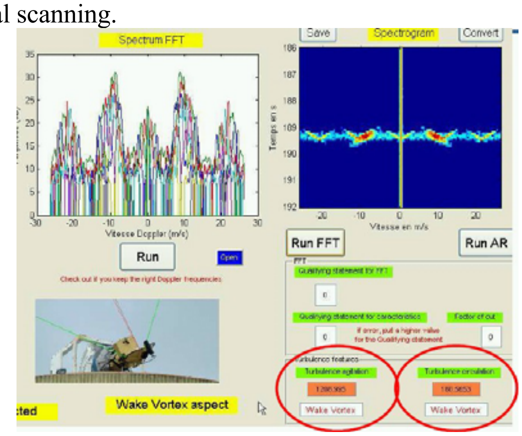


Fig. 33 : Wake Vortex HMI in vertical scanning mode

In the following figure, we illustrate connection between Doppler Entropy and Doppler spectrum for different Radar range cells corresponding to successive radar scans. We can observe that in the first scan, we have impulsion compression side lobes that pollutes adjacent cells in range. This effect, due to high signal to noise ratio of Wake Vortex signal, will be corrected in the future. We can observe than in the second scan the wake vortex altitude has decreased.

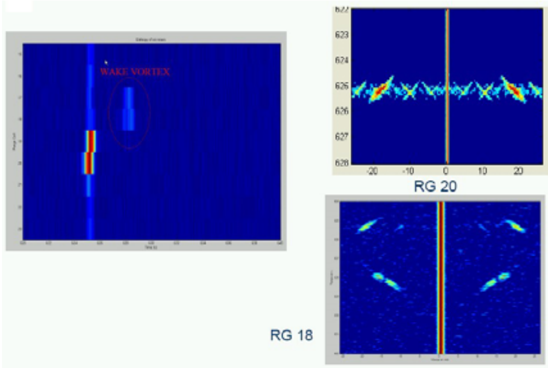


Fig. 34 : Doppler Entropy in Time/range axes (at left), and corresponding Doppler/Time Wake Vortex Spectrum for range 18 and range 20

In the following figures, we illustrate radar capacity to track from scan to scan wake vortex position in the glide slope. Drawback effect of impulsion compression side lobes in the first scan will be corrected in new version of the processing.

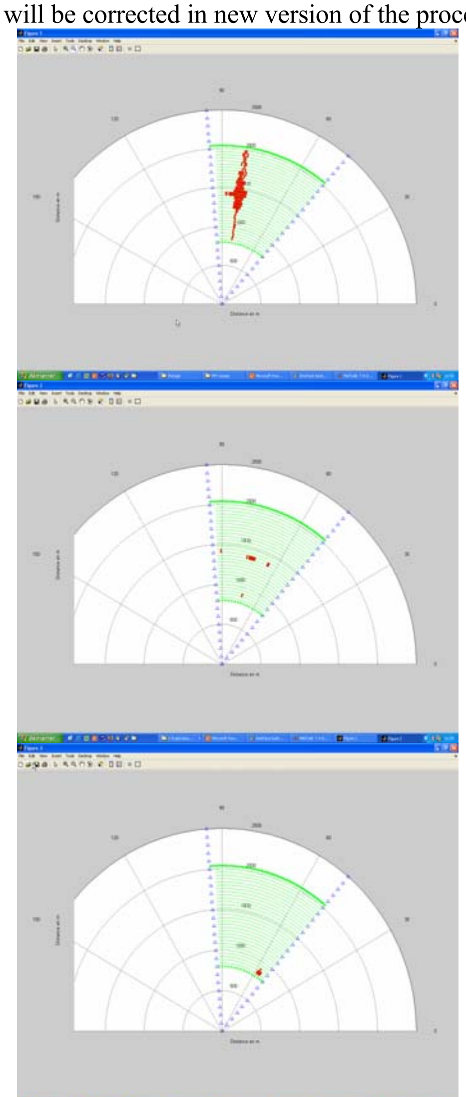


Figure 35 : Radar Wake Vortex detection in clear air from scan to scan at ILS interception area (altitude : 1500 m)

VII. New Joint Radar/Lidar Trials at Paris CDG Airport

In coordination with EUROCONTROL (Experimental Center, Bretigny), an additional campaign has been scheduled for end of November 2007 at CDG Paris Airport. This trial will be used to benchmark Radar and Lidar sensors and their capacity to monitor wake vortex in all weather conditions. Operationally, sensors will be configured and positioned to monitor airplanes wake vortices on the closest runway during take-off.

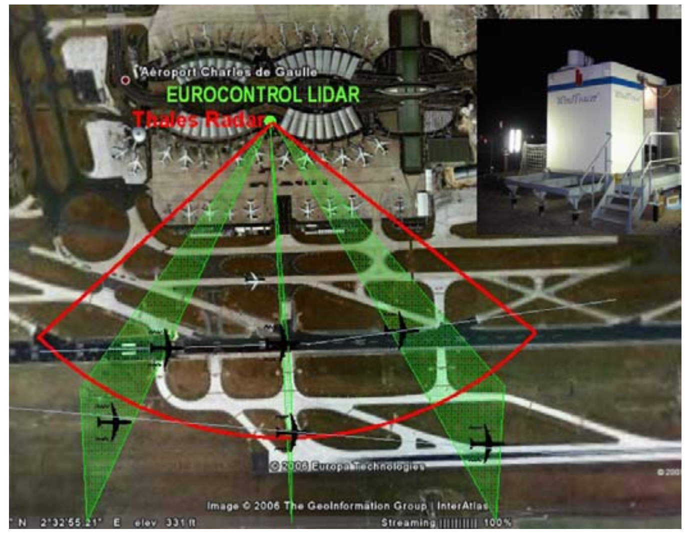


Fig. 36 : Radar/Lidar Benchmarking at Paris CDG Airport

VIII. Radar Technology for Wake Vortex Monitoring

Last August 2007, at the CLRC conference (Coherent Laser Radar Conference) in Colorado, Lockheed Martin has announced the development of an all weather system (WTDS : Weather Terminal Doppler System), combining 2 µm lidar Wintracer (and study of new 1.6 µm lidar) with a microwave X-band Radar to provide all weather alerting and covering dry air to heavy precipitation within airport terminal area. Software integration is ongoing and initial testing has been planned for Norman, Oklahoma during Summer 2007.

Fig. 37 : US Lockheed Martin X-band experimental pre-prototype Radar for Wake Vortex Monitoring

IX. CONCLUSION

THALES will propose to develop a pre-operational "wake vortex Radar Sensor" in the framework of SESAR and 2nd Call of 7th European Framework Program. Sensors benchmark will be addressed in European Wakenet3 network (7th FP).

In parallel, THALES is studying feasibility of an Integrated Wake Vortex Advisory System with low cost European sensors suite for airport equipment adapted for Closely Spaced Parallel Runway (e.g : Paris CDG Airport) including :

- **Temperature sensor** ; Sodar/RASS (PCS 2000 from Metek)
- **Wind Sensors** : Anemometors & UHF Radar Wind Profiler (WS425 & LAP3000 from VAISALA) & Lidar Wind Profiler (WLS7 from LEOSPHERE)
- **Wake Vortex Monitoring Sensors** : X-band Radar (BOR-A550 from THALES) & 1.5 μm Lidar (VLS14 from LEOSPHERE/ONERA)

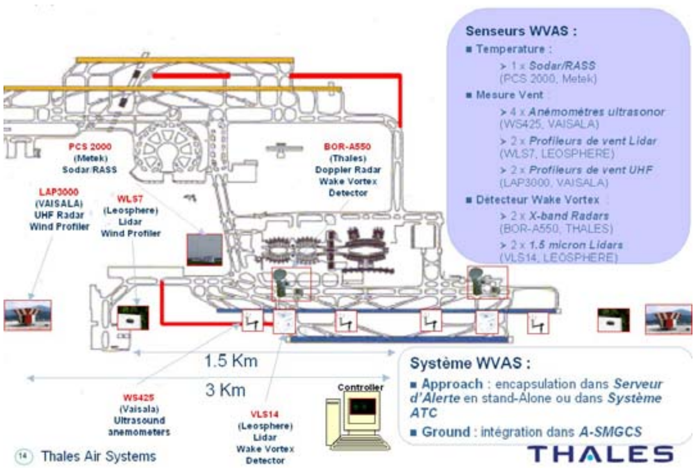


Fig. 38 : European Sensor Equipments (Wind & WV sensors) for Wake Vortex Advisory System deployment (e.g. : CDG Airport)

This Wake Vortex Advisory System could be integrated in ATLAS alert server (Advanced ThaLes Alerts Server), with an architecture declined from ATC-WAKE study [8][9], including Wake Vortex Sensors and Predictor. HMI for approach controller have been defined in ATC-Wake study.

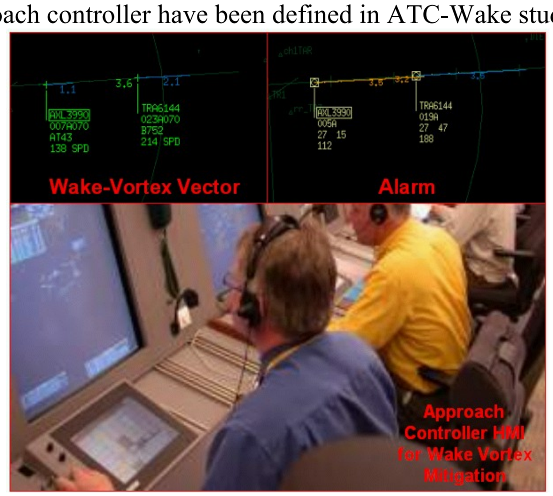


Figure 39 : Approach Controller HMI for Wake Vortex Alerts (ATC-WAKE)

ACKNOWLEDGMENT

Authors thanks ADP, DGAC and Eurocontrol Experimental Center (Bretigny), that have facilitated Thales Radar sensor deployment at ORLY airport and Paris CDG Airport for this X-band Radar trial campaigns, to prove Radar capacity of Wake Vortex Monitoring in all weather conditions.

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Evolving Air Traffic Scenarios for the Evaluation of Conflict Detection Models

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***Abstract*— Airborne separation assurance is a key requirement for Free Flight operations. A variety of conflict detection and resolution models are developed for this task. Due to unavailability of a common platform and limitations in current scenario generation methodologies, these models are not evaluated rigorously for complex traffic scenarios. In this paper we propose a methodology to evolve complex conflict scenarios and evaluate conflict detection models on them. The motivation is to identify the conflict characteristics where the conflict detection models can miss or wrongly identify a conflict event. A novel mechanism for evolving complex conflict scenarios is developed. This mechanism is integrated in a class B air traffic simulator which allows us rigorous testing of conflict detection models on a variety of conflict scenarios. Data mining techniques are employed to gain an insight into the failure dynamics of these models.**

Two conflict detection models, KB3D from NASA Ames and ASAS from NLR, are evaluated on safety metrics (false alarms and missed detects). Results shows that both the models generate a significant number of missed detect and false alarms when exposed to complex conflict geometries. Results also indicate that conflict detection models which employ nominal projection method are sensitive to the geometry between two conflicting flight specially if they are in a transition phase (climb or descent). They are also likely to miss those conflict events which are near the boundary of vertical and horizontal separation as well as when the convergence angle between two conflicting flight is wide.

***Index Terms*— Free Flight, Scenario Planning, Conflict Detection, Classifier Systems, Evolutionary Computation.**

I. INTRODUCTION

IN Free Flight, Airborne Separation Assurance Systems (ASAS) commonly known as conflict detection and resolution models will play an active role in separation assurance [1]. A variety of airborne conflict detection (CD) models are proposed in the literature and a detailed survey of them by Kuchar and Yang can be found in [2]. Most of these models are in concept stages, some of them are lab tested in simulation environment using hand design conflict scenarios [3], [4] and a very few in operational environments [5]. None of these models however, have been evaluated on a common platform for complex conflict scenarios [6] and their performance under non-nominal situations is unknown.

Since these CD models can be exposed to diverse operational modes and conflict conditions in a Free Flight environment, they need to be tested rigorously for robustness and assessed on safety measures before they can be put into operation [7]. As noted by Hokestra "the distributed nature and the infinite number of conflict geometries make it very hard to estimate the actual safety level compared to a centralized system. Because of the certification criteria as currently used by the safety-conscious aviation community, this proof might be required before the introduction of Free Flight" [8].

The shortcoming in evaluating the CD models for aviation use arises primarily due to two reasons: first a common platform (fast time air traffic simulators) where scenario generation and evaluation processes are integrated are not readily available and secondly, current methodologies of generating/developing air traffic conflict scenarios are highly tedious and time consuming [9], which limits their rigorous evaluation. Recorded air traffic data do not contain aircraft-to-aircraft conflicts and other non-nominal scenarios since any such situation is already resolved by the controllers. The rare recorded air traffic accidents are in the order of 10−10 per flight
hour making it almost impossible for the existing fast time simulators to asses such event in recorded air traffic data [10].
It is highly desirable to have a methodology to generate, evaluate and evolve increasingly complex conflict scenarios for CD models on a common platform in an integrated manner. Apart from rigorous evaluation another advantage of such a methodology would be to contemplate over the conflict characteristics data and provide insights into the anomalies or complex conflict geometries where different CD models fail i.e. produce false alarms or missed detects. In particular, one would like to figure out if:

1. A relationship exists between conflict characteristics and the false alarms or miss detects generated by various models? And
2. Do different CD models fail in varying or similar conflict scenarios?

An answer to the first question can help to improve existing algorithms or develop new ones. The answer to the second question can help in deciding which algorithm to choose in a particular conflict scenario.

A. *Paper Contributions*

In this paper we:

1. present an integrated methodology to generate, evolve and evaluate complex conflict scenarios,
2. evaluate CD models using this methodology on standard safety metrics, and

3. provide an insight into the failure dynamics of the CD models.

First, to automate the process of scenario generation we break from the classical approach of pre-scripting scenarios and instead use an evolutionary computation approach using Genetic Algorithms (GA) [11]. Our approach is to play “Devil’s Advocate” where complex conflict scenarios are deemed “fitter individual” having increased likelihood of survival to the next generation in the evolutionary process of GA. These scenarios are fed into a fast time air traffic simulator for execution and evaluation the performance of CD models. The objective of the evolutionary process is to evolve increasingly complex conflict scenarios where CD models incur maximum failure (in terms of evaluation metrics). Finally, a data mining technique based on learning classifier systems (LCS) [12] is used to find the patterns in the conflict characteristic data.

This paper is organized as follows, next section briefly covers the mechanism of CD models, techniques in scenario planning, genetic algorithms and use of data mining techniques, while the following section presents the methodology of evolving conflict scenarios using genetic algorithm. Evolution of complex scenario is successfully demonstrated and CD models are evaluated on them. Finally, we investigate patterns and conflict characteristics using data mining techniques and conclude with our findings.

II. Background

A. Conflict Detection Models

Conflict detection in the aviation domain is a widely studied field and in the wake of Free Flight initiatives this topic has gained high importance. The mechanism of the majority of the models (including those investigated in this paper) is based on the nominal projection method [2]. An example would be to extrapolate the aircraft’s position based on its current velocity vector. The nominal projection method is straightforward, and provides a best estimate of where the aircraft will be, based on the current state information. In situations where aircraft trajectories are very predictable (projecting few seconds into future), a nominal trajectory model is may be quite accurate.
However, most of the existing CD models are inadequate in addressing issues like complex conflict scenarios and robustness to failure [2]. A consistent methodology for evaluating and validating CD models is recommended for implementing most effective systems in the field [6], [2].

B. Evaluation methodologies for Conflict algorithms

CD models are evaluated quantitatively or qualitatively. In qualitative evaluation, they are examined with real time traffic with human-in-loop (HIL) in a high fidelity simulation environment [13] mainly looking at feasibility and implementation issues. In quantitative evaluation, they are examined using a range of scenarios in a fast time simulation mode [10] mainly looking at algorithm performance. Previous investigations using quantitative evaluations of CD models have established “missed detect” (MD) and “false alarms” (FA) as primary metrics to quantify the reliability of a conflict probe [14], [15]. We have used the same metrics and their implementation is discussed in a later section.

C. Scenario Planning

Scenarios are a core component of simulation and evaluation of advance concepts in Air Traffic Management (ATM). They are of high importance in providing a robust feedback on whether an ATM concept can be implemented in the operational environment [16].
Existing methodologies on scenario generation focuses on pre-scripted scenarios where the designer pre-selects the scenario characteristics (mainly conflict) and then generates scenarios, which are then fed into the main simulator for execution and analysis [16]. This approach is costly both in terms of time and money. Another approach is to use the recorded air traffic data and modifying it to induce conflict situations. These conflict situations are achieved either by incorporating pseudo-conflicts where the current separation standards are increased to induce conflicts [17] or by altitude shift where the altitude of aircraft is manipulated to generate conflict situations [18]. Another methodology developed by the U.S. Federal Aviation Administration (FAA) involves the use of genetic algorithms to time-shift flights taken from recorded data to produce specified conflicts [19]. These methodologies maintain realism in present day traffic but in the future, airspace structure might be completely different (or even absent), as compared to the current system. Time shifting and altitude shifting can induce conflicts but the structured nature of traffic flow is still retained in them. In a symposium, organized by Eurocontrol Experiment Center and FAA on best practices for scenario development, it was highlighted that in order to evaluate CD models for scenarios with varying degrees of complexity, the “scenarios need to be focused on repetition, replication, evolution, and performance measurement” [16].
Our approach in conflict scenario generation is to use conflict characteristics at the closest point of approach (CPA) between two conflicting aircrafts and then workout their trajectories in past using vector calculus and basic trigonometry. Such that, when the two aircrafts, activated at a specified birth points at a given time following a specified trajectory, will meet each other at a CPA with specified conflict characteristics. Initially these conflict characteristics are generated at random, then using the CD model evaluation metrics as fitness criterion; increasingly complex conflict scenarios are evolved. So the models are repeatedly exposed to evolving and increasingly complex conflict scenarios.

D. Genetic Algorithm

Genetic Algorithms (GAs) [11] are probabilistic search algorithms that derive their mechanism from evolutionary process of natural selection. Despite early reservations about application of GAs in air traffic domain, there is currently a growing interest in their application. Gas have been success fully applied in air traffic planning [20] and conflict detection and resolution [21] to name a few. GAs start with a randomly generated population of n chromosomes (candidate solutions to a problem). The suggested solution (conflict characteristics) is encoded into the "genes" of the chromosome. It then calculate fitness f (x) of each chromosome x in the population. It then selects a pair of parent chromosomes from the current population, the probability of selection being an increasing function of fitness. New offspring are formed by using genetic operators like crossover and mutation. This process is repeated until a new population is evolved. Then for the new population the same set of operations is repeated. Each iteration of this process is called a generation and the entire set of generations is called a run. GA provides advantages over Monte Carlo techniques in our case as it can quickly scan a vast solution set. Bad proposals (scenarios where CD models did well) do not affect the end solution negatively as they are simply discarded.

In our approach, every chromosome represents an air traffic scenario, where each conflict event in the scenario is represented as a gene of the chromosome. Initially random conflict scenarios are generated and CD models are evaluated for each scenario on the given objectives using fast time simulator. Based on the fitness of a scenario and using genetic operators, fitter scenarios are evolved over generations. The idea is to evolve more complex conflict scenarios as evolution progresses. For the GA process we have used Non-dominated sorting genetic algorithm (NSGA-II) [22] which represent state-of-the-art in the evolutionary multi-objective algorithms.

E. *Mining Scenario Data*

In section I we highlighted the need of understanding the conflict data and set out the objectives. To rephrase, we would like to anticipate a relationship between the model failures and the scenario characteristics and see if different models fail in varying scenarios. Given the large amount of scenarios generated by the process it becomes unwisely to perform this analysis manually and identify characteristics of interest. Consequently, we sought the help of data mining tools to find out the answers to our hypotheses.

Data mining techniques are concerned with finding the useful information or interesting patterns within large sets of data that can help in analysing the underlying problem from different perspectives [23]. The objective is to find a generalized concept from the given data which can then be applied to future cases with high predictability. By applying such techniques we hope to summarize and categorize the characteristics of high risk scenarios. In this work we have used a real time LCS based signature extraction system (UCSSE) [24] for this task. LCS [25] are genetics based machine learning technique that use simple if-then type of rules to learn a concept description. The signature extraction system adaptively identify and extract the most generalized and accurate rules.

III. Methodology

Our methodology of evolving complex scenarios using GA, evaluating CD models using ATM simulator, and analysis of conflict characteristics is shown as a process flow diagram in figure 1. By encoding conflict characteristics in chromosomes, wide range of complex conflict scenarios can be evolved independently. NSGA-II provides straight forward evolution process and fast time simulator provides the evaluation environment for the CD models. After every run the MD, FA and Valid Alerts (VA) are recorded along with conflict characteristics. At the end of evolutionary process this data is processed using data mining techniques (LCS). Patterns are identified and inferences are made on the performance of CD models. The GUI of air traffic simulator also provides an opportunity to replay the scenarios, with human in loop, for a detailed analysis of factors which lead to algorithm failure (not discussed in this paper). Each component of our methodology is described in the following subsections.

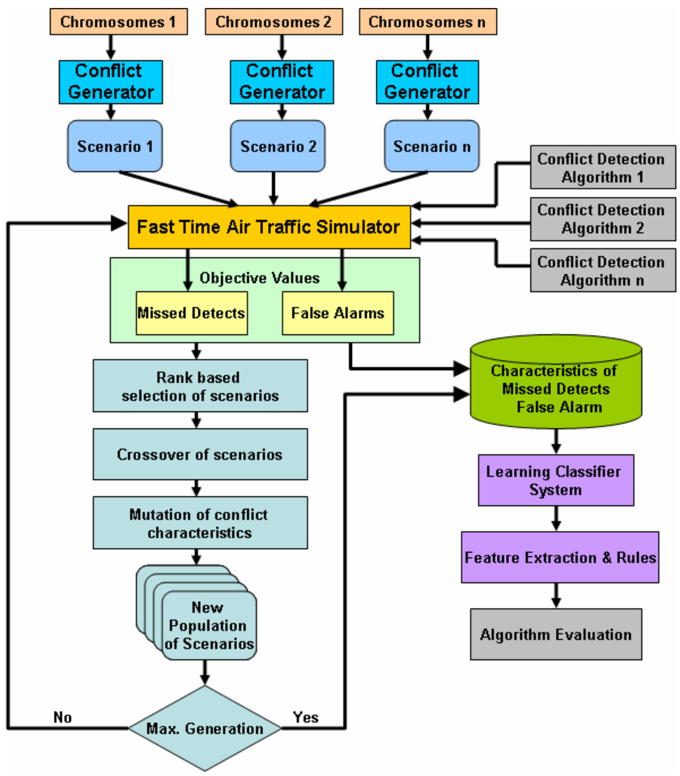


Fig 1.A Process flow diagram for generating, evolving conflict scenarios and evaluating CD models

A. *Characteristics of a Conflict Scenario*

The performance of a CD model primarily depends upon the characteristics of the conflict scenario. A head-on conflict between two cruise level aircraft may be easy to detect as compared to an in-trail conflict between two descending aircrafts. Based on [26] we determined that following conflict characteristics at the CPA are sufficient to generate initial birth points of the two conflicting aircrafts.

- Horizontal separation (HS) violation: The horizontal distance between two aircraft at the closest point of approach.
- Vertical separation (VS) violation: The vertical distance

between two aircraft at the closest point of approach.

• Conflict geometry Intruder (CGI): The phase of intruder aircraft at the closest point of approach. This can be climb, cruise or descent.

• Conflict geometry Ownship (CGO): The phase of ownship aircraft at the closest point of approach. This can be climb, cruise or descent.

• Conflict angle (CA): The relative conflict angle between the two aircrafts at the closest point of approach. These characteristics are then encoded into each gene which represents a conflict between ownship and intruder. They are initially generated at random within the given bounds and then taken care by the evolution process as described later.

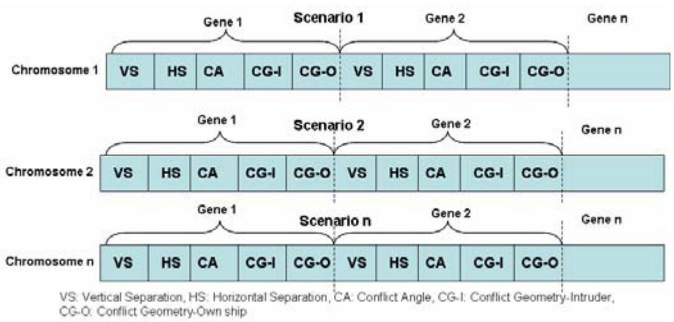


Fig. 2. Encoding of conflict characteristics in a linear chromosome structure

B. *Encoding scenarios into chromosomes*

A real valued representation with linear chromosome structure is chosen to represent a conflict scenario, where every gene of the chromosome represents a conflict between a pair of aircrafts as shown in figure 2. Every gene in this chromosome encodes the characteristics of a conflict identified in the previous section. If there are 50 genes in a chromosome, then the number of aircraft in the airspace will be at least 100 as each gene represents a unique pair of conflict. Thus a set of chromosomes can be seen as several air traffic scenarios, where the events of conflicts are characterized by the genetic encoded information in the respective chromosome. Before initializing the chromosomes following steps are performed:

• Define the airspace region: The extent of research airspace in 3D. It is defined by start and end latitude, start and end longitude and an altitude range vertically. All conflict events are simulated within this region.

• Define the simulation run time: The time window in which the aircraft are activated and deactivated. However, a scenario is run until the last flight in the airspace is deactivated.

• Define the airspace density: The total number of aircrafts to be executed in a scenario. The actual density however, depends upon the activation time of flights.

• Define the minimum and maximum range for the variables: The upper and lower bounds for the conflict characteristics to be encoded. For HS violation: {0.0 nm - 5.0 nm}, for VS violation: {0.0 ft - 1000 ft}, for CA :{0 degrees - 180 degrees}, for own ship and intruder geometry we randomly selected a floor value in the interval {1.0 and 3.0} so that 1 represents climb, 2 represents cruise and 3 represents descent Then each alle in the gene is initialized randomly within the given bounds, A chromosome with its genes after initialization is illustrated in figure 3.

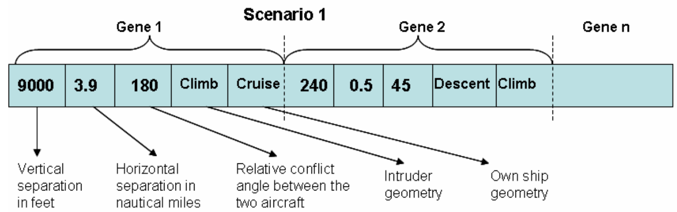
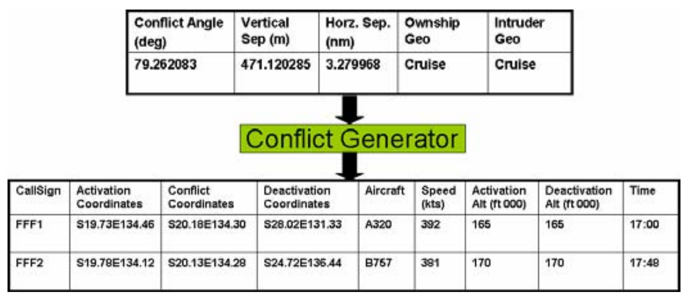


Fig 3. A chromosome with its genes after initialization

C. *From chromosomes to air traffic scenarios*

We developed an algorithm (conflict generator) to workout the trajectories of conflicting aircrafts given the conflict characteristics at their CPA. First, the intruder position in 3D is generated at random within the research airspace. Then a cylinder of the dimensions of horizontal and vertical separation violation is formed around it. The trajectory of the ownship is worked out using the equations of tangent to the surface of this cylinder. Their initial and final positions longitude and altitude) are then worked out based on their conflict geometry and conflict angle at the CPA. The speed and activation time is computed such that the two aircraft meet each other at CPA with the desired conflict characteristics.

Figure 4 shows an example of the flight plans of two conflicting flights, generated by the conflict generator, given the conflict characteristics. Flight plans generated by the conflict generator consists of a unique call sign, activation coordinates, CPA coordinates, and deactivation coordinates, aircraft type, activation flight level, deactivation flight level, speed, and activation time.



Conflict Angle (deg)	Vertical Sep (m)	Horz. Sep. (nm)	Ownship Geo	Intruder Geo
79.262083	471.120285	3.279968	Cruise	Cruise

CallSign	Activation Coordinates	Conflict Coordinates	Deactivation Coordinates	Aircraft	Speed (kts)	Activation Alt (ft 000)	Deactivation Alt (ft 000)	Time
FFF1	S19.73E134.46	S20.18E134.30	S28.02E131.33	A320	392	165	165	17:00
FFF2	S19.78E134.12	S20.13E134.28	S24.72E136.44	B757	381	170	170	17:48

Fig. 4. Flight plans of a pair of conflicting flights generated from the conflict characteristics

D. *Measures of fitness*

Fitness of a scenario is based on the performance of the CD model on it. If a CD model performs well on a scenario then its fitness is low and the fitness is high if a CD models performed poorly on a scenario. We have used missed detects and false alarms as a primary metrics to quantify the reliability of a CD model. They are defined as follows:

• Missed Detects (MD): This metric represents the number of potential conflicts which resulted in a separation violation but the CD model failed to detect them.

• False Alarms (FA): This metric represents the number of conflict alerts that didn't actually materialized into a separation violation, but the CD model labelled them as potential conflicts.

Since we are working on inverse problem here, so higher the missed detects and false alarms better scenario it is. The objective functions can be defined as a maximization problem where the objective is to maximize the events of MD and FA in a scenario.

E. Scenario evaluation in fast time simulator

For execution of scenarios and evaluation of CD models we used Air Traffic Operation and Management Simulator (ATOMS) [27]. ATOMS is a 4D, point-mass model based, 5 degree of freedom air traffic simulator which provides an experimentation environment for advanced air traffic management concepts. A variety of conflict detection and resolution models are implemented in ATOMS. The flight plans which form an air traffic scenario are fed into ATOMS that execute them in a fast time mode. Aircrafts are flown in autopilot mode and arrives at CPA with desired conflict characteristics. The

CD model may or may not identify potential conflicts based on its mechanism. In this study the protected zone around an intruder aircraft is defined as a cylinder with radius of 5 nm and a height of 2000 ft (based on currently used separation minima).

IV. Experiments Design

A. Candidate algorithms

Two CD models are identified in ATOMS for evaluation purposes. The KB3D algorithm of NASA Ames, US developed by Dowek, Munoz, and Geser [28] which is an extension and optimization of Billimoria's 2D conflict detection algorithm [29] and Air Borne Separation Assurance System (ASAS) of National Aerospace laboratory, Netherlands (NLR) developed by Hokestra [8]. Principal modelling method in both the algorithm is nominal trajectory propagation where the current states are projected into the future along a single trajectory, without direct consideration of uncertainties. Both the algorithms are purely geometric in nature and do not undertake any uncertainty. The conflicts are detected based on comparing predicted trajectories of the two aircrafts without taking into consideration any other uncertainty. Both algorithms detect conflicts in horizontal as well as vertical plane. However, the two algorithms differ in their methodology of computing the predicted minimum separation distance and processing of state vectors for detecting conflicts. The look ahead time is set to 8 min, time to closet point of approach : 5 min, probe frequency : 5 sec, horizontal Separation : 5.0 nm, vertical separation : 1000 ft and probe range to 80 nm.

Since both algorithms are state based, no turn maneuvers are modelled. As having frequent turn would only lead to large number of FA. Flights are enroute phase only, so no top of climb or top of descent are computed. Flights activate at their designated birth points and deactivate at designated points as per their flight plan data. Only conflict detection component of CD model is switched on and aircrafts fly over with out resolving conflicts.

A generic airspace (S32.0E142.0, S38.0E150.0) over east coast of Australian flight information region is used for air traffic simulation. Flight activation time is [1 sec - 1200 sec (20 minutes)]. For GA the number of generations is set 100 and population size is set to 50, implying that there are 50 scenarios in each generation. In each scenario there are 100 aircrafts with at least 50 conflicts. More conflicts can also results due to overlapping trajectories (if any). Standard NSGA-II simulated binary crossover (SBX) operator and polynomial mutation are used for real-coded chromosomes. The probability of crossover of real variable is set to 1.0. Probability of mutation of real variables is set to 0.1. Experiments are run on a SGI Altix 3700 Supercomputer. For 5000 scenarios comprising of 500,000 conflicting flights in a fast time simulation mode, total run time is approx. 89 Hrs.

During the simulation run (executing a scenario), potential conflicts detected by the algorithm, as well as actual "conflict happened" events along with their conflict characteristics are recorded. At the end of every scenario execution the two sets are processed to obtain the MD, FA and VA. Each data set consists of varying number of cases belonging to each of the three classes (i.e. FA, MD and VA) and their associated characteristics. Thus the problem of learning a model for the failure of CD algorithms can be framed as a 3-class problem. The goal is to extract the patterns or scenario characteristics where CD models produced FA and MD, distinguishing them from the correctly predicted outcomes i.e. the VA. Here we adopted the 3-class problem approach so that maximally non-overlapping patterns or rules can be found for FA and MD classes. Further we found that for almost all of the FA cases either the HS or VS parameters were outside the bounds i.e. 5 NM and 1000 ft respectively of conflict zone. This implies that a concept learning technique will learn a trivial model of type: IF HS > 5nm && VS > 1000ft, hiding information about all other parameters. Subsequently, to remove this artefact we removed the HS and VS attributes from both data sets.

The data is fed into UCSSE in the form of feature vectors. Each feature vector, or an instance, in our case consists of the attribute values of a conflict event recorded at a particular time stamp with its corresponding label obtained by the air traffic simulator. The attributes used in each feature vector are listed in the previous section. Two more attributes, azimuth angle and relative velocity are also recorded as they form a vital component in CD model's mechanism. The labels correspond to three possible outcomes of the prediction of a CD model i.e. VA, FA and MD. Since UCSSE is a supervised learning system the labels are provided along with the instances during the learning or training phase. The system outputs its model as a set of self-explanatory if-then rules. The accuracy of these rules is then evaluated using the data without labels

V. Results

We first investigated the results on the evolutionary process to ascertain that our mechanism is actually evolving complex conflict scenarios. Figure 5 shows, how initially, when the conflicts scenarios were generated at random, the two CD models performed very well giving very low MD and FA, but as the evolution progressed and complex conflict scenarios are generated, the number of MD and FA increases. At the end of 100 generation, in the final population, we can see that the two algorithms have high number of MD and FA. We then ascertain that wether evolutionary process suffers from early convergence, either by concentrating the flights in a narrow region within the airspace to generate complex conflicts or by "squeezing" the flights activation time in a small time window to generate cascading conflicts.

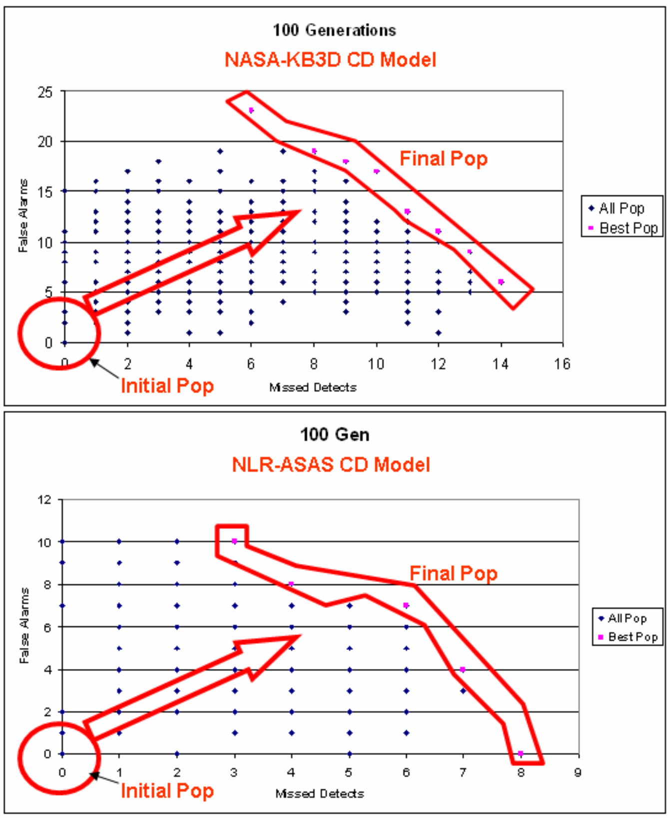


Fig 5. Higher number of MD and FA are generated by the two CD models as evolution progress.

Figure 6 and figure 7 shows respectively that the flights activation time and conflict locations in the initial and final population are well distributed. We then looked into how the individual conflict characteristics were evolved over generations. Figure 8 shows the frequency of flight conflict geometry in the initial and final population during the evolution process. It can be seen from figure 8 that transition level (climb or descent) flights are more likely to generated missed detects and false alarms.

Figure 9 shows the frequency of horizontal separation (nm) at CPA in the initial and final population. It can be seen from figure 9 that conflicts which have horizontal separation close to 5nm are evolved over generations. Similarly in figure 10, which shows the frequency of vertical separation (ft) at CPA in the initial and final population, it can be seen that conflicts with vertical separation close to 1000ft are evolved over generations. Figure 11 shows the frequency of conflict angle at CPA, it can be seen that conflicts with shallow and very wide angles are evolved over generations. These charts do provide an insight into the conflict characteristics where the CD models have poor performance, but it require detailed analysis of the data to derive meaningful and specific results.

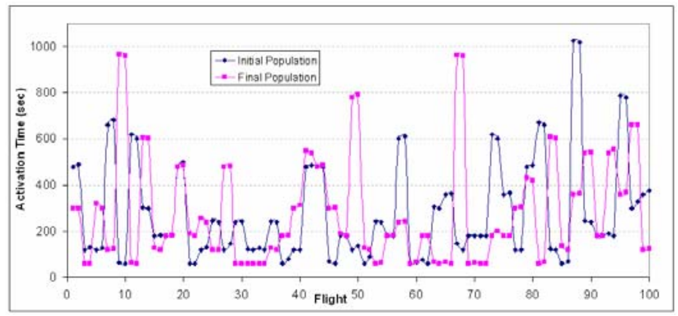


Fig. 6. Distribution of Flight activation time in the initial population and final population during evolution process.

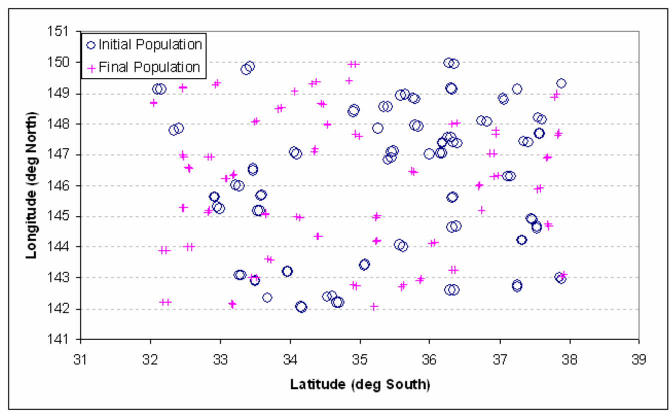


Fig. 7. Distribution of Conflicts over the research airspace (East coast of Australia).

So we then employed the UCSSE on the conflict characteristics data generated by the two models. Table I summaries the classification model evolved by UCSSE for each of the CD models. The number of rules shows the compactness of the model whereas the model accuracy represents its correctness or the generalization ability. The results are average of 30 runs. Note that each training data set consisted of large number of instances (8152 for KB3D and 9360 for ASAS) but a much smaller number of rules are obtained that capture the concepts in the data. This in itself signifies an underlying relationship between the scenario parameters and the failure classes. Table II provides only the most accurate rules obtained by UCSSE that capture the scenario characteristics where the two CD models produced FA and MD. Az is the azimuth angle, Rv is the relative velocity between two aircrafts, Go is ownship geometry, Gi is intruder geometry and Ar is the relative angle at CPA between two conflicting flights. For each rule its condition, predicted class and accuracy is provided. 100% accuracy means that the rule correctly predicted all cases it matched whereas a drop in accuracy occurs due when a rule wrongly predicts some of the cases.

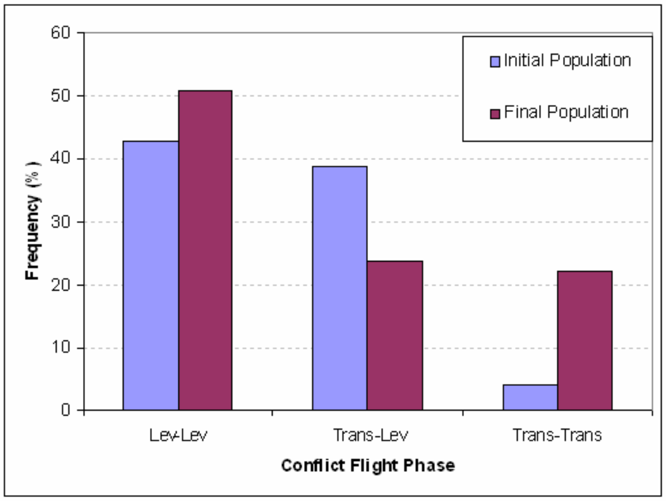


Fig. 8. Frequency distribution of flight conflict geometry in the initial population and final population during evolution process

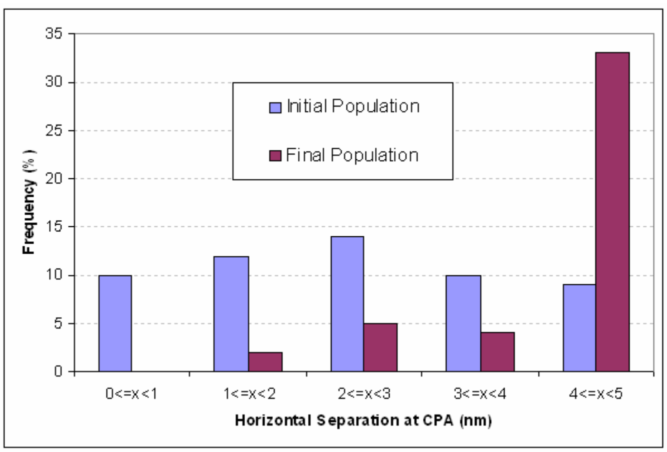


Fig. 9. Frequency distribution of horizontal separation (nm) at CPA in the initial population and final population during evolution process

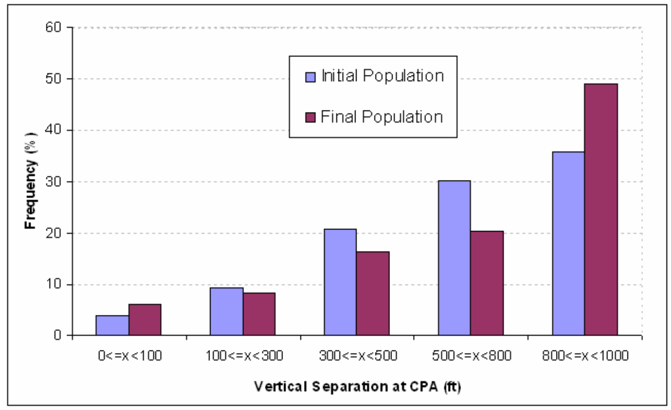


Fig. 10. Frequency distribution of vertical separation (ft) at CPA in the initial population and final population during evolution process

For NASA-KB3D CD model it can be seen from one of the conditions in table I that it can give MD when relative velocity between two conflicting aircraft is greater than 19.4m/s and less that 50.3m/s and ownship geometry is cruise or descent and intruder geometry is cruise. For FA one of the condition is when the relative velocity is greater than 151.3m/s and relative angle between the two aircraft is greater than 211.2 deg and geometry of ownship is descend.

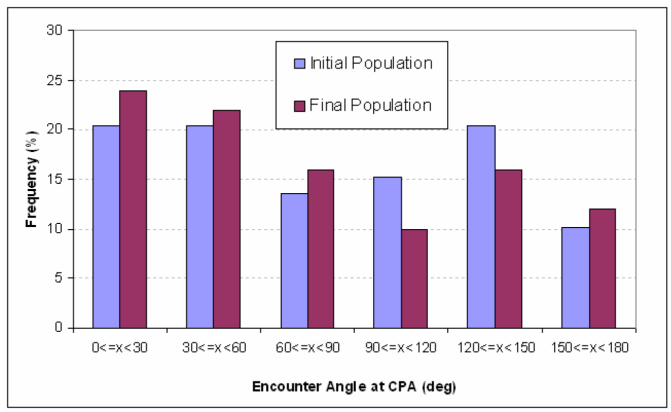


Fig. 11. Frequency distribution of conflict angle (deg) at CPA in the initial population and final population during evolution process.

TABLE I
NUMBER OF RULES AND TEST ACCURACY USING UCSSE

	NASA-KB3D			
	MD	FA	VA	Overall
Number of Cases	2551	2497	4312	9360
Number of Rules	16:40	16:33	5:50	38:23
Model Accuracy	99:49	92:83	73:29	85:67
	NLR-ASAS			
Number of Cases	2759	1349	4044	8152
Number of Rules	52:33	10:40	15:57	78:30
Model Accuracy	90:02	94:48	82:04	86:83

For NLR-ASAS algorithm we can infer that it can generated missed detects when azimuth angle is greater that 32.6 deg and relative velocity is less than 153.0 and conflict angle between the two is greater than 12.3 deg and less than 102.6 degrees and geometry of ownship is cruise or climb and geometry of intruder is cruise or descend.

For both the algorithms we found that in a conflict scenario when ownship is descending the CD model is more prone to generate FA. Similarly when the relative conflict angle between the two is very wide then they are likely to generate MD.

VI. Conclusions

Our methodology of using evolutionary mechanism was successful in evolving complex conflict scenario. The two CD models were applied on these scenarios and their performance on given metrics was evaluated. The characteristics of those conflicts where the models generated MD and FA were analysed using classifier system. The patterns that emerged by assimilating the condition was that when ownship is in the descend mode then the CD models are more likely to generate false alarms. Wide conflict angles between two aircraft can lead the CD models to generate missed detects. The analysis done in this paper for identifying conflict characteristics to evaluate CD models may not be conclusive, in that only a small sample of conflict characteristic data is used for extracting the patterns. However, it serves as a proof of concept for our hypotheses. A detailed analysis and fine tuning of the mining tools would lead to more accurate and meaningful patterns that can be used to identify the gaps in existing CD models and how to improve them. Also note that an offline data analysis is carried out in this work. However, given the incremental nature of LCS a real-time switch can be modelled that can select the best CD model in a particular conflict scenario. We leave this work for future.

TABLE II
SOME OF THE MOST ACCURATE RULES OBTAINED USING UCSSE.

No.	Condition	C	Acc
	NASA-KB3D		
1	*Az < 144:3 ∧ Rv = 0:4 ∧ Go is CR*	*MD*	97:2
2	*or DS ∧ Gi is CR Rv = 0:4 ∧ Ar >*	*MD*	96:2
3	*63:7 ∧ Go is CR or DS ∧ Gi is CR*	*MD*	93:4
4	*19:4 < Rv > 50:3 ∧ Go is CR or DS*	*MD*	90:1
5	*∧ Gi is CR Az = 0 ∧ Rv < 236:0 ∧*	*F A*	96:6
6	*Ar < 115:4 ∧ Go is CR ∧ Gi is CR*	*F A*	95:7
	or CL Rv > 151:3 ∧ Ar > 31:2 ∧		
	Go is DS 93:6 < Rv > 500:6 ∧ Go		
	is CL ∧ Gi is DS · · ·		
	NLR-ASAS		
1	*Az > 100:3 ∧ 83:1 < Rv > 429:5 ∧ 28:4 < Ar > 46:5 ∧ Go is CL ∧ Gi is CR or CL*	*MD*	*100:0*
2	*75:5 < Az > 95:3 ∧ Rv > 214:7 ∧ Ar > 137:2 ∧ Go is CR or CL ∧ Gi is CR or DS*	*MD*	*100:0*
3	*12:9 < Az > 62:1 ∧ Rv > 325:9 ∧ Ar > 138:3 ∧ Go is CL ∧ Gi is CR or DS*	*MD*	*100:0*
4	*Az > 32:6 ∧ Rv < 153:0 ∧ 12:3 < Ar > 102:6 ∧ Go is CR or CL ∧ Gi is CR or DS*	*MD*	*100:0*
5	*Az < 91:7 ∧ 93:4 < Rv > 265:4 ∧ Ar > 177:9 ∧ Go is CR*	*F A*	*100:0*
6	*Rv > 403:1 ∧ Go is DS ∧ Gi is CR or DS*	*FA*	*98:9*
7	*Az < 112:1 ∧ Rv > 252:7 ∧ Go is DS*	*F A*	*93:8*

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EUROCONTROL

On Linkage-Based Clustering Approach and Air Traffic Pattern Recognition

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Abstract—**The paper introduces a methodology and key concepts aiming at identifying flows structures and assessing their interdependencies. These flows structures are the basis on which Logical Functional ATFCM Areas (LFAAs) are defined allowing the anticipation of regions of strong network effect interactions and provide a means for the definition of a predictive function around which Collaborative Decision processes can be organised in order to reduce complexity and increase efficiency of the Network Management.**

***Index Terms*—Air Traffic Pattern Recognition, Data Clustering, Linkage Algorithms, Logical Functional ATFCM Areas**

I. Introduction

As stated in the SESAR (Single European Sky ATM Research) programme [1], the determination of solutions that cope with capacity/demand imbalances should be designed through "a pan-European planning and coordination between all stakeholders, both at the strategic and tactical levels".

To fulfil this aim, the future ATM processes should provide a predictable and stable system that "simplifies and increases the transparency of collaborative decision making processes".

This goal would be delivered through a collaborative layered planning [2] at local level supported by a Network Management Function which determines, balances, refines, and then optimises capacity and demand on the basis of common situational awareness of the ATM picture and network effects resulting from the stakeholders' decisions.

This fundamental principle implies for the Network Management Function to have the means for a clear collaborative and information sharing process, including the identification of the involved actors, the appropriate solutions, and the assessment of their possible interdependence enabling to anticipate the network effect resulting from these solutions.

The first part of this paper aims to provide key concepts and approaches that enable to draw a picture of the traffic demand structure by identifying the main flows and measuring their interdependencies. The proposed approach uses data clustering techniques to group elementary sectors depending on traffic demand connectivity criteria.

The second section shows how the identification of demand structures can be used to design homogeneous ATFCM areas, called Logical Functional ATFCM Areas which delineate regions in which network effect resulting from local ATFCM measures is potentially significant. A draft set of LFAAs has been identified so far and is presented to better illustrate the followed approach. Further work, including the calibration of the clustering model and operational evaluation is in progress.

II. Demand Pattern Identification

A. Objective

The main objectives of the demand pattern identification is to provide a global and complete vision of the main flows structure composing the traffic demand over the ECAC area and also to quantify the interdependence among the flows in an anticipate way.

The outcome of this first stage allows the manipulation of flows that are implicitly associated to a set of flights and their crossed airspace areas. This approach offers a rich and aggregated means for the analysis of potential interactions between airspace areas and subsequently the design of functional airspace boundaries.

The present section proposes an approach aiming at defining flows structures on the basis of data clustering techniques.

B. Clustering techniques

Clustering is the process of organising objects into groups whose members are similar in some way. Applying clustering process to flows identification consists in grouping elementary sectors which are connected in a certain way that determines the shape of the flows and their connectedness.

A great number of well-known clustering techniques have been developed [3] but the approach used to cluster the sectors and define the flows shapes is based on agglomerative hierarchical clustering algorithms [4].

These algorithms follow the same conceptual framework which is presented below. Some adaptations have been introduced to cope with the flows definition problem:

1. Start with N elementary sectors placed into a list of singleton sets $S_1, S_2, \ldots, S_n$ and an $N \times N$ symmetric connectivity matrix $D = \{d_{jk}\}$, where d_{jk} is given by the expected common demand crossing the sectors x_j and x_k.

2. Select a connectivity threshold (a common demand value) which allows to trade off between the number of formed clusters and compactness of each cluster.
3. Find the pair of clusters $\{S_i, S_j\}$ that is connected at a higher level than the connectivity threshold. Then replace S_i and S_j with $S_i \cup S_j$ in the clusters list and update the connectivity matrix values.
4. Repeat step 3 until no more clusters can be merged.

The major difference between the agglomerative clustering algorithms is the definition of the connectivity function used in step 3 to evaluate the connectivity level between two clusters. In the case of flows identification, connectivity function will determine the shape and the density of the flows.

Single linkage, complete linkage and average linkage are the three relevant linkage-based agglomerative algorithms that have been implemented in the context of demand pattern recognition and consequently determine the shape of the identified flows.

Depending on the linkage mode, the connectivity function providing the value of between-clusters connectivity is given for each pair of clusters $\{S_i, S_j\}$ by:

Single Linkage: $d_s = \max_{x_i \in S_i, x_j \in S_j}(d_{i,j})$

Complete Linkage: $d_c = \min_{x_i \in S_i, x_j \in S_j}(d_{i,j})$

Average Linkage: $d_a = \dfrac{1}{|S_i||S_j|} \sum_{x_i \in S_i, x_j \in S_j} \sum d_{i,j}$

Single linkage: with this method, the fusion of a sector (or a clusters of sectors) with a cluster at a given connectivity level, only needs that one element of each of the two clusters be linked to one another at this level.

Complete linkage: the algorithm allows a cluster to be merged to another at a given level only if all the elements of the cluster are linked to all the elements of the other cluster at this connectivity level.

Average linkage: this method allows two clusters to be merged at a given level if the average of connectivity values links the clusters at that level

III. Demand Structure Identification

ATFCM is a complex system composed of strongly interacting elements, which can be sectors, flows, traffic volumes or any airspace volume that is constrained by a limited capacity and may require being protected by applying an ATFCM measure such as ground delay, re-routing or level capping.

Evaluating network effect resulting from ATFCM measures requires analysis means that identify and quantify the interactions over the elements of the system.

The paper focuses on the related effect among elementary sectors. An indicator is defined to quantify the connectivity among the sectors, the **common demand**, which is given by the number of flights per day crossing any pair of sectors.

Evaluating this indicator for each pair of sectors over the ECAC area and representing the corresponding values in a matrix provide an overall vision of the connectivity level between the sectors. Moreover, linkage algorithms allow the identification of structures based on the existing main flows and assess the overall architecture of the network providing a quantitative evaluation of its flows components and their relationships.

In the following, an example of demand structure and dependencies identification is described in order to provide an overview of the potential use of clustering techniques in the framework of demand pattern recognition. Linkage algorithms have been implemented within the Visualisation and Analysis of the Network Effect Tool (VANET) developed at EEC.

Table 1 presents the experiment scenario which is applied to a week-end day in July 2006. The experiment uses the complete linkage mechanism, which in this example will merge sectors that share at least 80 flights two by two.

Table 1
Clustering Parameters

Algorithm	Merged elements	Linking criteria	Thresh value
Complete Linkage	Elementary sectors	Common demand	80

The complete linkage algorithm enables to extract elongated structures (cf. Fig. 1) representing the path followed by a set of flights representing a flow. The length of the extracted flows increases as the connectivity threshold relaxes.


Fig. 1. Flows Map

The matrix on Fig. 2 shows the result of clustered sectors and the corresponding common demand values. It can be noticed that values inside each cluster/flow are all greater than 80.

The matrix on the left Fig. 3 provides an aggregated representation of the previous map and matrix, where rows and columns are the flows with their respective colour. The values are average common demand corresponding to the level of internal connectedness of the sectors belonging to the same flow (the main diagonal) and the demand that two sectors belonging to two different flows may share on average.

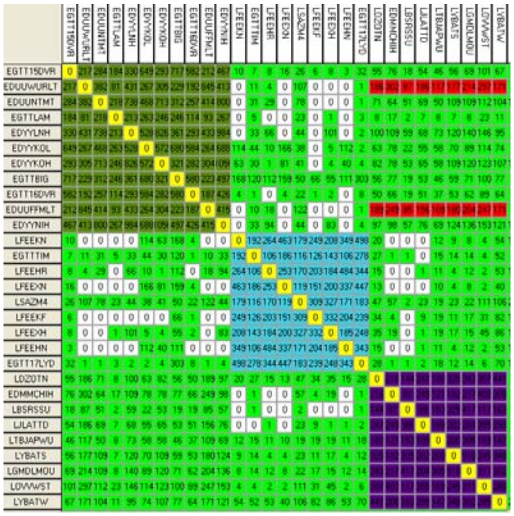

Fig. 2. Arranged common demand matrix

The matrix on the right provides an additional indication on the number of sectors that are crossed by a pair of main flows. In that case, two sectors are crossed by the flows 0 and 2: EDUUWUFLT and EDUUFFMLT, which dependence values highlighted in red on the matrix of Fig. 2, are all greater than 80.

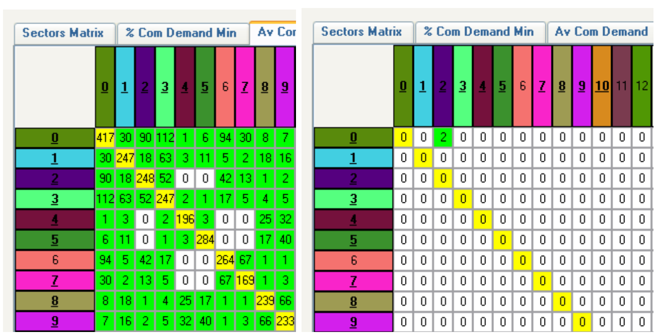

Fig. 3. Flows relationship matrix

These aggregated matrix representations provide a meaningful means to quantify the structure of the network and evaluate the dependence among the main flows.

The following section will describe a methodology based on average linkage algorithm to identify homogeneous functional areas for which ATFCM measures could be applied ensuring that network effect is localised inside the defined area and is almost inexistent outside.

IV. LFAAs Concept Definition

This section presents a methodology initially described in [5], which enable to anticipate the identification of groups of quasi independent ATFCM bodies termed by Logical ATFCM Functional Areas (LFAAs). The identification of such areas aims to improve the coordination within the ATFCM decision processes and consequently network efficiency.

Furthermore, the proposed method has to be calibrated and validated with the help of operational network manager experts in view of a potential implementation in the framework of future ATM systems modelling.

A. *LFAAs objectives*

This section aims at answering the question of what are the potential applications of Logical Functional ATFCM Areas concept in the operational context.

The identification of two areas referred as the South-West and North-East axis in which a set of Collaborative Decision Making (CDM) procedures have been set up is an illustration of what would be the LFAAs and their use [6].

LFAAs identification method can be generalised to the ECAC area as a basic concept for the validation activities and more precisely for those related to NOP building and collaborative decision making processes.

Therefore, the LFAA concept could contribute to improve the efficiency of ATFCM CDM processes by providing guidelines for reducing the number of relevant actors involved in the implementation of pre-defined scenarios.

Furthermore, for a given pre-defined scenario or any ATFCM measure, the definition of LFAAs boundaries together with the evaluation of network effect indicators would continuously enrich NOP processes with structured and relevant input data that help to improve the network performance and efficiency.

Finally, LFAAs definition could also simplify the CDM process in tactical phase by quickly and fully anticipating and evaluating the interactions within the network and consequently by applying the appropriate ATFCM measures that ensure network efficiency.

B. *LFAAs definition*

Regarding the ATFCM system objectives, the concept of LFAAs would be inevitably related to the identification of the traffic demand structure, which is provided by the main flows directions/axis. Main flows represent the strongest links between sectors, while minimising the network effect between each other. In addition, it is also to consider the possible re-routings of these flows.

Hence, LFAAs are expected to be formed by the main flexible and relatively independent flows linked by potential re-routings.

V. LFAAs Design Process

The designing process addressed in this paper concerns the identification of LFAAs at the strategic ATFCM phase.

This section presents the experimental framework and the design process for which each step is illustrated by the corresponding network decomposition result.

A. *Designing principles*

Designing LFAAs will follow an iterative process based essentially on a statistical approach but also on the expertise of network managers that helps to refine and validate the first statistical modelling iterations.

It is important to recall that the designing approach presented in this paper, concerns the strategic phase of ATFCM system. This will require the definition of stable entities based on the identification of existing demand patterns.

B. Experiments Parameters

In table 2 are given the parameters for the first two iterations

TABLE 2
CLUSTERING PARAMETERS

	Merged elements	**Linking criteria**	**Thresh value**
Iteration 1	Elementary sectors	Common demand	320
Iteration 2	Main Flows	Average common demand	120

of the design process.
The use of those parameters will be explained when detailing the process iterations.

C. Designing Iterations

1) Iteration 1: Grouping the elementary sectors

The first step aims to identify the basic flows corresponding to the strongly connected sectors.

Hence, the identification of a basic flow consists in merging the highly connected sectors within a same group (main flow).

In order to ensure the stability of the clustering process, the average linkage principle will be used: for a given common traffic demand threshold average linkage method allows a

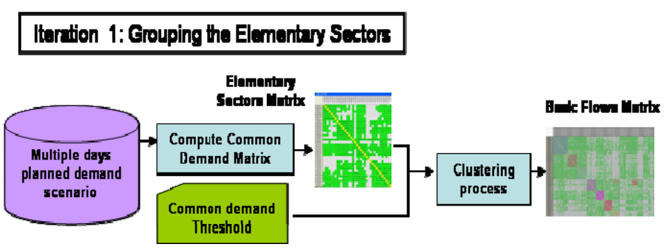

Fig. 4. Basic Flows Identification Process

sector to join a group (main flow) if the average common demand between this sector and all members of the group is greater than the given threshold.

It is worth to notice the importance of selecting an appropriate common demand threshold value, since it determines the characteristics of the decomposition and the connectivity of the formed flows

Several experiments have been achieved so as to determine the best threshold value regarding the number of sectors merged and the internal connectivity of the formed flow. The connectivity indicator is given by the average common demand of the sectors composing the flow and is displayed in the main diagonal of the interdependence matrix.

The selected threshold for identifying the basic flows at the first iteration is established at 320 flights for the eight days scenario (or 40 flights per day on average), as presented in Table 2.

Therefore, the main flows resulting from the average linkage clustering process would be composed of sectors having shared demand higher than 320 flights on average.

The mains flows and their remaining interconnectivity values (i.e. average common demand) are displayed in the map and the matrix of Fig. 7 respectively.

The large values of the internal connectivity displayed on the main diagonal of the matrix can be compared to the inter flows connectivity values.

In addition, iteration 1 seems to succeed in the identification of the basic flows that compose the North-East (NE) axis (Cf. Flows number: 0, 3, and 6 in Fig. 6) and the South-West (SW) axis (Cf. Flows: 1, 9, and 10). These axes are two regions currently managed through collaborative decision processes to resolve the airspace bottlenecks occurring in these areas. The identification of such regions based on structure of the demand will be the input for the assessment of LFAAs identification approach. More details will be provided further.

2) Iteration 2: Grouping the basic flows

Having the set of basic flows and their interdependence

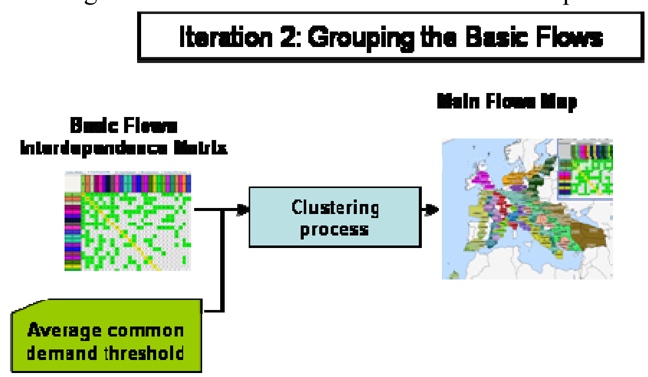

Fig. 5. . Main Flows Identification Process

matrix the second iteration will merge the highly connected basic flows and form the main flows.

The process uses the average linkage principle to group the basic flows with a threshold of average common demand of 120 flights.

The resulting main flows are displayed in Fig. 7. It could be noticed that the interdependent flows of "South-West" and "North-East" axis, previously identified, have been merged at the second iteration, since their interdependence values, at the first iteration were higher than the fixed average demand threshold.

3) Iteration 3: Grouping the main flows

Starting from elementary sectors and arriving to main flows, the merging process will carry on recursively until the LFAAs are formed. At the current stage, most of the possible re-routing should have been included within their respective main flow. However, some possible re-routings occurring between two main flows and establishing a functional relationship between these flows will complete the LFAAs design process by grouping the "re-routable" main flows.

Two grouping approaches can be used depending on the availability of expertise concerning each main flow. The first

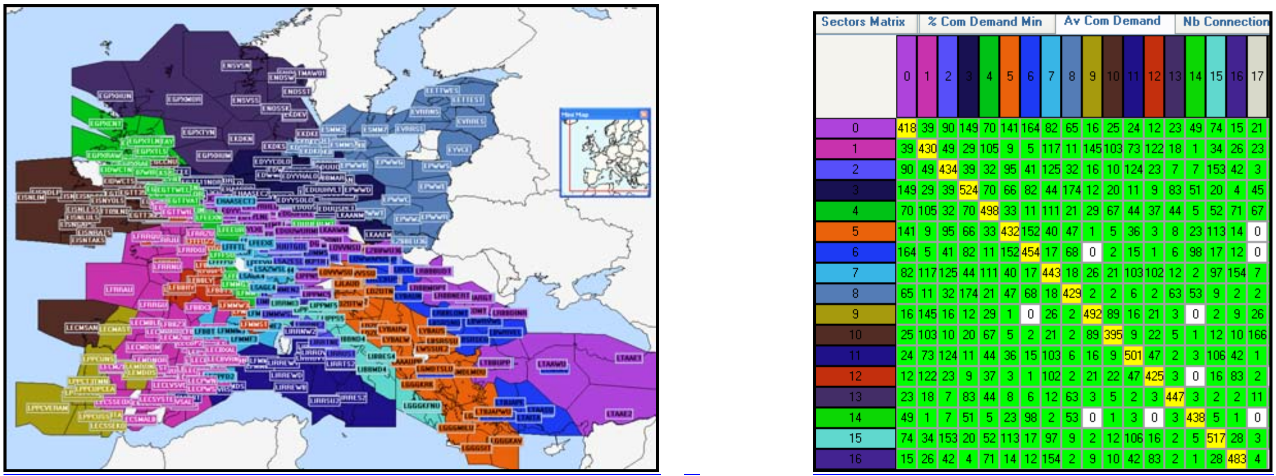

Fig. 6. Iteration 1 - Basic Flows Identification and Resulting Interdependence Matrix

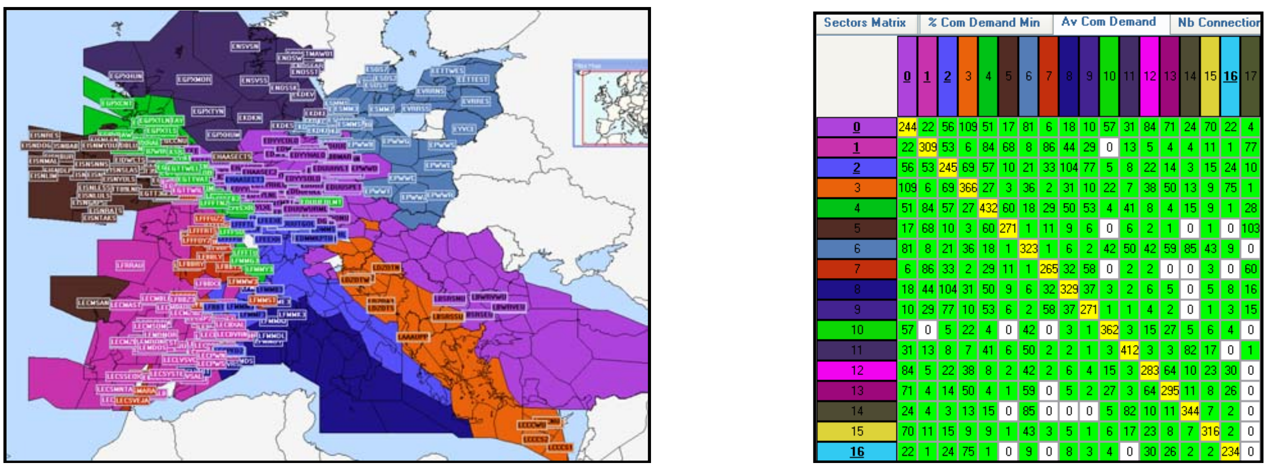

Fig. 7. Iteration 2 - Main Flows Identification and Resulting Interdependence Matrix

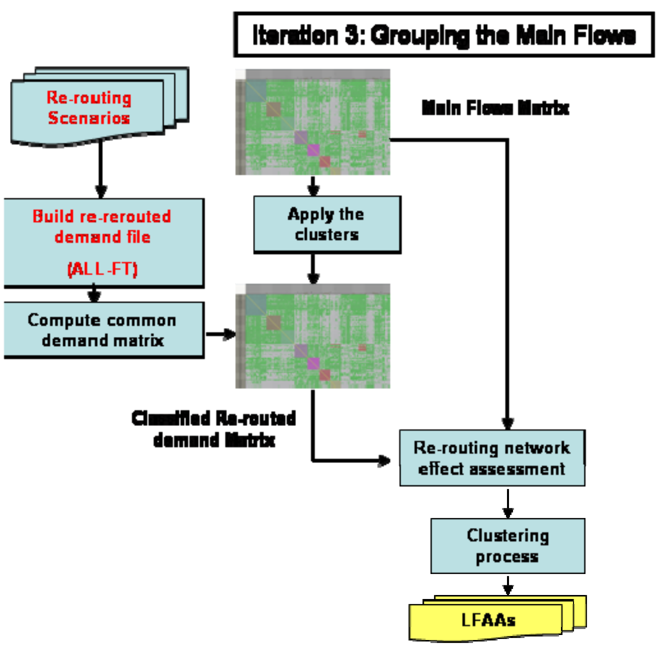

Fig. 8. Composing the LFAA's

approach is operational: since the number of flows is reduced, the flows could be merged on the basis of network manager experience and knowledge.

If the possible re-routings between the main flows cannot be assessed by operational expertise, a statistical approach will be used; this approach is displayed on Fig. 8. Starting from past traffic demand, the process identifies all the possible re-routings by origin/destination pair. Then, all the scenarios will be used to build a virtual traffic demand file and its associated common demand matrix. When this matrix is ordered according the main flows matrix, the possible routes between the main flows will be identified.

4) *Iteration 4: Calibration of the model*

When LFAAs process is completed, the aim of the calibration phase is to compare the ATFCM regions identified operationally (SW and NE regions) with those calculated by the design process (Cf. Fig. 9) and adjust the common demand threshold value according an iterative process, described below, until the appropriate thresholds are identified.

D. *LFAAs operational assessment*

The objective of this phase is to validate the operational feasibility of the LFAAs design approach. While, the calibration phase compares calculated LFAAs with existing

ATFCM regions, the operation assessment will confront new calculated LFAAs to the operational point of view.

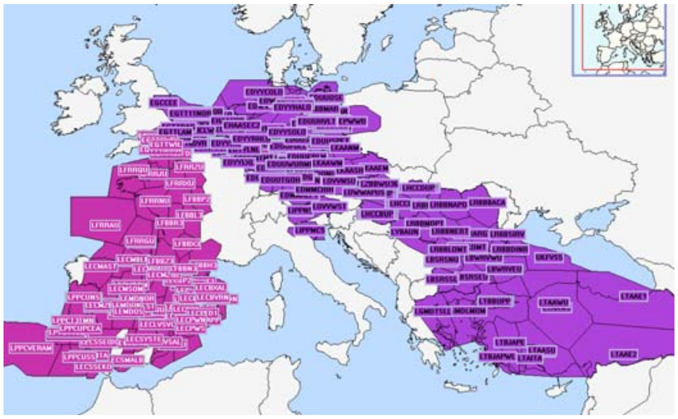

Fig. 9. SW and NE axis issued from the LFAAs design process (Iteration 2)

When the designed LFAAs are not in adequacy regarding operational considerations, the design process must be refined in order to take into account the relevant operational constraints that have been identified during this phase.

E. LFAAs sectors typology

Finally, after the identification of new LFAAs and their operational validation, each resulting LFAAs is then composed of re-routable main flows which in turn are formed by strongly dependent elementary sectors ensuring a high internal functional connectivity.

However, even if the merging process is based on the maximisation of internal dependencies and the existence of potential re-routings, it will remain some inter LFAAs connections corresponding to the common demand of sectors that belong to several LFAAs at the same time.

In order to assess the interconnectivity between LFAAs, a typology of the sectors composing the LFAAs is proposed.

Two categories of sectors are distinguished: weakly connected sectors named "flow oriented sector" and strongly interconnected sectors named "connecting sectors".

Connecting sectors will be assigned a sector/LFAA connectivity indicator value which assesses the degree of membership of the sector to each LFAA.

The result of the overall LFAAs design process is illustrated within the model of Fig. 10**.**

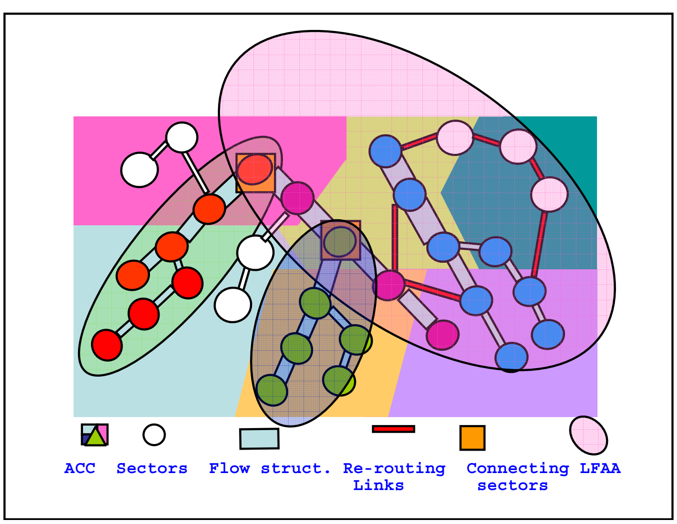

Fig. 10. A model for LFAAs Structure

VI. Conclusion

The paper proposes an initial research work representing a key modelling approach for the identification of airspace regions that strongly fit the air traffic pattern.

The design of the LFAAs is a first application of this approach aiming to anticipate the identification of groups of homogeneous ATFCM bodies and the identification of the inherent collaborative networks.

Besides LFAAs design, the approach offers a structured information related to network effect which would contribute to create more explicit and efficient Collaborative Decision processes.

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A Taxonomy of Dynamic ATC Visualizations

Christophe HURTER, Stéphane CONVERSY

Abstract— **Air traffic control systems display information using multiple visual variables. The research described in this paper is an initial effort to develop a theory-driven approach to the characterization of user interfaces. We will focus on the displayed visual object and deliberately leave aside the interaction. In this article, we depict the state of the art in data visualization, and we characterize these systems using the Card, Mackinlay and Bertin model. This work helps characterize images more precisely, refines our understanding of the transformations of the raw data that generates them, as well as the role of perception in the interpretation of visualization.**

Index Terms— **Information Visualization, taxonomy, graphical coding.**

I. Introduction

Air traffic control aims to maintain the safety for passengers and goods. This task puts them in a complex decision making system. They communicate with pilots using clearances to keep minimal separation of aircraft. The context is highly dynamic; data presented to the air traffic controller come from manifold sources: flight plan, radar data, data link, metrological data, and supervision systems. The decision must be planned in real time and frequently updated. This is the reason why the air traffic controllers' display must be sharp, and must reduce their cognitive workload.

The displays used by the air traffic controllers involve many animated visual entities. They are constrained by precise rules of representation. The richness of these re-presentations highlights the paucity of tools currently available to differentiate them. The increments of such instruments are numerous, in terms of validation, design and safety. The objective of this article is to establish the basis to study representations, to find out methods of characterization that would allow comparisons between representations, and eventually to assess them.

II. Information Visualization

Information visualization (IV) is an expanding field of research, but rare are those who have formalized its non-artistic approach. In the wide range of existing visualization methods, very few of them are actually supported by scientific considerations, and even fewer have been formally evaluated in a rigorous context. Some are starting to address this issue [[25], [28]] and some have summarized it in a framework [[18]].

The Works of Bertin [[1]], act as a reference: "the graphic" is the mono-semantic visual representation of data. We can contrast his formalism with music or modern abstract art, in which the represented data is polysemic (the perceiver can have different interpretations).

The aims of visualization techniques have been fairly well established [[26]]. According to Bertin, the visual data representation has three issues; store data, spread information (the communication is carried out with known data in advance), process information (the handling and the perception of the data allow the analysis and the resolution of the problem). Bertin made simple observations of visual displays. He introduced seven visual variables: position, size, shape, orientation, brightness, color, and granularity. Granularity is often translated as texture, but it really means granularity (as in the granularity of a photograph). Granularity in this sense is also related to the spatial frequency of a texture. Thus, he formulated issues of visual decoding and proposed techniques for enhancing it. But he eschewed principles of vision theory. For psychological theories on Bertin's work, we can consult Kosslyn's books [[13]]. Kosslyn, for instance, introduced the compatibility rules, which leads the semiotic to correspond to the meaning of a graphical representation.

Wilkinson [[28]], among other things, has extended the classification system of Bertin. He prefers the word aesthetics to describe an object in a graphical system, because the word perception is subjective rather than objective, and perception refers to the perceiver rather than the object. Aesthetics turns graphs into graphics so that they are perceivable, but they are not the perceptions themselves.

Mackinlay continued Bertin's work by presenting tools allowing the generation and the validation of graphic interfaces [[15]]. It develops in particular a graphical language to codify a representation.

Tufte illustrated the possible application fields of IV in geographical, historical, economic situations [[26]].

Shneiderman classified visualizations according to the number of dimensions of the displayed data, to the data representation structure (temporal, multi-dimensional, tree, networks). He continued his work by identifying seven minimal tasks to ensure the visualization of the data [[24]] (overview, zoom, filter, details on demand, relate, history, extract).

Card and Mackinlay (C&M) carried out a taxonomy of various charts of information in the form of a table [[5]]. This taxonomy is partially based on the theory of Bertin. C&M applied it to twelve well-known visualizations, such as the ordered matrices [[1],[19]], TreeMap [[11]] or ConeTree [[21]]. This article will detail their work in the following sections.

Tweedy [[25]] doesn't use the noun visualization, she prefers 'externalizations' because it indicates the cognitive role of interactive visual representation. This article introduces one kind of visualization characterization, without the interactions available in visualization. This work focuses on visual representation, therefore interaction will be dealt with in another article.

One of the most important tasks in Data Visualization is to understand the cognitive process involved in the perception of a representation. To reach this goal, the design space must be precisely depicted using taxonomy or a generative procedure. The next section will describe the dataflow formalism.

III. DATA FLOW MODEL

Card, Mackinlay and Shneiderman contribute greatly to our knowledge in the field of visualizations [[6]]. They created a model (Fig. *1*) which describes visualizations as a data processing sequence from the raw data to the display. The processing is based on structures of intermediate data which is easy to handle by the user. Chi detailed the various stages of this model [[7]]. This data flow model is widely used.

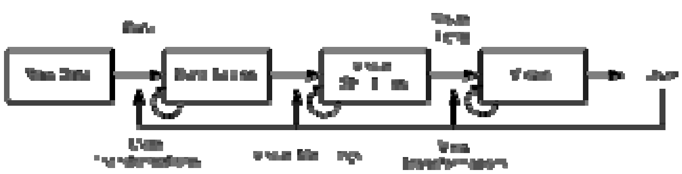

Fig. 1 : Schematic Dataflow of Information Visualization [[5]]

This model is based on the management of a data flow. It is used in many toolkits (InfoViz **[**[10]**],** prefuse, VTK, Tulip, Pajek…) and visualization software (SpotFire **[**[1]**]**, ILOG Discovery **[**[2]**]**, nVizN **[**[28]**]**…).

A. *Data type*

We define the attributes as the typed date from the dataset, and the properties, the visual representation of a data e.g. if we use the color to code the AFL (actual flight level) then the AFL data are the attribute and the color is the (visual) property.

The major distinction we can make for attributes is whether their values are:

- Nominal: are only equal or different to other values (e.g. aircraft call sign),
- Ordered: obey a < rule (e.g. an aircraft's number in the landing sequence),
- Quantitative: can be manipulated by arithmetic (e.g. the aircraft speed).

The quantitative type can be split into two parts: Interval and Ration.

The Interval can derive the gap between values but cannot be null, e.g. the time lapse between 7.00am and 8.00am is the same than 14.00am to 15.00am but we cannot say that 15.00am is twice 7.00am.

The ratio type is the full expressive power of real numbers. The table summarizes the different terms used in the literature.

TABLE 1
DATA TYPES

Bertin [[1]]	**Stevens** [[23]]	**Ware** [[27]]
Nominal	Nominal	Category
Ordinal	Ordinal	Integer
Quantitative	Interval	Real number
	Ratio	

B. *Data structure*

Bertin has suggested that there are two fundamental forms of data: data values and data structures. A similar idea is to divide data into entities and relationships. Entities are the objects we wish to visualize, and relations define the structures and patterns that relate entities to each other.

He defines five data structures: linear, circular, ordered tree, un-ordered tree, and volume. The data structure is the link that clusters the data. In the ATC world, the call sign links the radar data. If we display over time the position of an aircraft, we display a linear data structure.

C. *Data transformation: the metadata*

There is a common misconception about metadata. In a database, metadata are the explanation of a database field (e.g. AFL is the actual Flight level of the aircraft in a dataset). But in IV, Metadata mean data derived from other data, this is a transformation that creates new data out of the existing data.

Tweedy found four types of data transformations (*Fig. 2*):

- Values to Derived Values (e.g. mean processing)
- Structures to Derived Structure (e.g. sorting variables)
- Values to Derived Structures
- Structure to Derived Values

Transformations that switch between value and structure are more complex. Schneiderman, Card and Mackinlay have explained them [[6] p 21-22].

Metadata and raw data are intrinsically different but their representation problems are the same, thus we won't make any special survey for metadata.

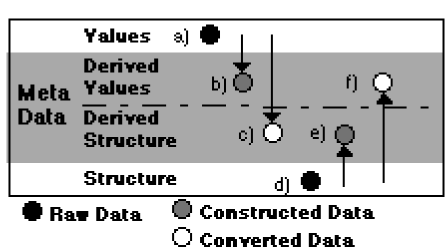

Fig. 2 : Types of Information Represented [[25]]

D. *Data sources*

The data source is the same for manifold ATC visualizations. We are not exhaustive, but mainly, the radar (aircraft position received by the ground radar station), and flight plan (the aircraft path from its take-off to its landing) are the principal data sources. ODS is the main French radar view displayed for the air traffic controllers; Aster is a vertical view of the current flying aircraft, Maestro is an Arrival manager, and ERATO displays future aircraft conflicts.

Fig. 3 : ATC Data source

ATC visualizations display the same information, thus to compare them we need very precise tools.

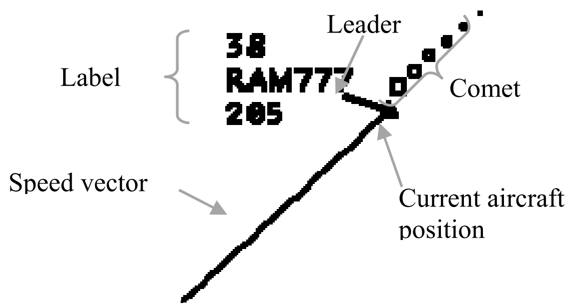

Fig. 4 : the radar track

The *Fig. 4* displays the terms used to depict the radar track.

E. *Supervision*

Graphics, according to Bertin, have at least three distinct uses (c.f. introduction): store, communicate, discover.

The images of the ATC world are not visualizations dedicated to exploration. They are described as supervision, because the input data change independently of the user. But the user can perform actions on the system; in principle, he tries to improve it. Such action has different levels of criticism: just convenient (giving a direct routing) to critic (avoiding minimum aircraft separation).

The ATC data structure is linked to the attribute named callsign.

F. *Implementation*

The validation of this transformation model was carried out using software. This software respects the data processing sequences of the data of Fig. 1. It makes it possible to describe the radar image using a dataflow and connections with the visual variables of Bertin (Figure 3).

IV. Metrics and Perceptual Task

Visualization can lead to efficient, accurate visual decoding of encoded information, but may lead to inefficient, inaccurate decoding.

Bertin identified three distinct levels for a visualization analysis: elementary (for a single item), intermediate (for a group of items), and overall (for all the data).

One of the most basic problems humans encounter when using computers is to know what to do to get the computer to solve a particular problem. The second problem is to understand the computered results, what is the graphical meaning of the displayed data. Norman [[16]] identified these two problems and named them the gulf of Execution (how to solve a problem with a computer) and the gulf of Evaluation (what do I see).

The air traffic controller uses supervision interfaces, thus the gulf of execution is reduced. The field of action is limited, and the displayed information fits the interface goal. This chapter will focus on the gulf of evaluations especially on the metrics to compare visual entities.

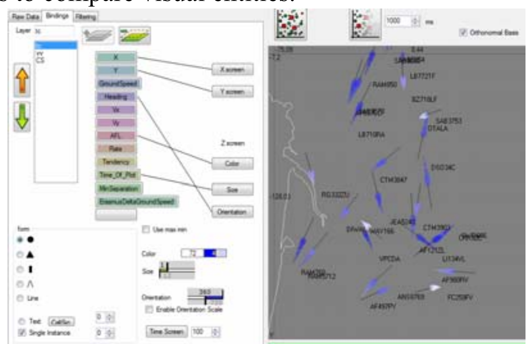

Fig. 5 : dataflow implementation

Cleveland, McGill and then Mackinlay [[15]] built scales of expressivity (monosemic, but dependant on a precise graphical language) and effectiveness (depend on the human perceptual capabilities) to assess alternative designs (*Fig. **6***). This scale depends on the data type. The visual property higher in the chart is perceived more accurately than those lower in the chart. The grey items are not relevant to that type of information. The quantitative data type ranking as been experimentally verified by Cleveland [[9]]. Independently of the data type, the best way to represent the data is to code it with a position on a scale. If we want to represent the speed of an aircraft (quantitative data), we can use the length of a line (speed vector). The aircraft position number in the landing sequence (Ordinal) is better coded using the color saturation than length.

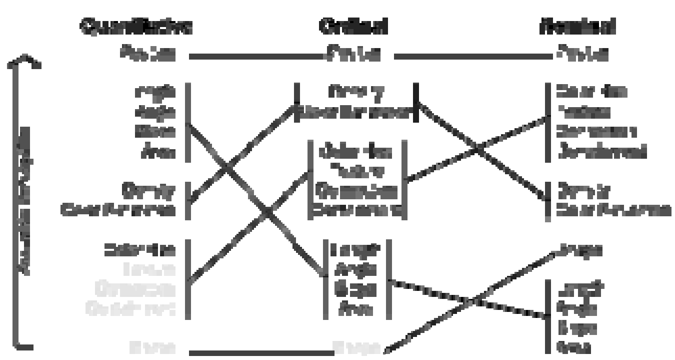

Fig. 6 : Mackinlay ranking of perceptual task [[15]]

This ranking was built for statistical graphs. Air traffic control displays, and other iconic representations of data addressed quite different tasks. But this is a starting point of research.

A. *Is Text the most powerful representation?*

Despite the fact that the text involves perceptual and cognitive processing that helps one to decode a graphic in the same way that perceiving color or pattern does, the text entity isn't listed in Mackinlay's perception ranking. "Images are better for spatial structures, location, and detail, whereas words are better for representing procedural information, logical conditions, and abstract verbal concepts." Ware [[27] p301-307].

Graphical perception is highly parallel which works on visual properties such as position and color, but has limited accuracy. Text representation is accurate but is limited in capacity. The cognitive workload is very high when we are reading a text.

Paivio used the dual coding theory to explain the difference between text and graphical perception [[17]].

B. *Stimulus vs. sensory*

The Difference Threshold (or "Just Noticeable Difference") is the minimum amount by which stimulus intensity must be changed in order to produce a noticeable variation in sensory experience. Weber, a medical professor, discovered that the intensity of stimuli may not be linearly related to sensation. The relation between the stimuli and the sensation is formalized in the Weber–Fechner law. Stevens' power law is generally considered to provide a more accurate and general correlation.

Cognitive psychologists have recently turned away from psychophysics toward a more integrated, ecological approach. Because all psychophysical approaches isolate stimuli in order to examine their psychometric functions, the results apply only to certain restricted, indeed artificial, situations. The context is entirely applicable.

Hence, the Kabuki [[2]] project (DTI R&D) aims to propose methods and tools to assess ATC interfaces. The design and the checking of the interfaces allow anticipating the problems of perception and coherence which appear only during the users test, but also, provide the metric to adjust the relative values of parameter settings of the visual objects.

C. *Distance and evaluation*

Cleveland and Mackinlay rate the position on the scale as the best way to represent a quantitative dimension visually (Fig. 6). This reflects the research finding that points or line lengths placed adjacent to a common axis that enables judgment with the least bias and error. But it depends on how far a point, line, or other graphic is from a reference axis [[14], [22]].

D. *Animation*

Animation can be done on two levels: with the raw data, and with the visual representation. With the raw data, new data must be created with interpolation. If the animation is based on the visual structures, each entity must have a sole identifier.

Animation helps perception with little cognitive workload. Patterns in moving data points can be perceived easily and rapidly. Given the computing power of modern personal computers, the opportunity exists to make far greater use of animation in visualizing information.

V. TAXONOMY

The value of a picture in the communication process is well recognized and one hears the old adage "a picture is worth a thousand words".

Visualization techniques attempt to provoke intuitive appreciation of the salient characteristics of a data set.

It is necessary to use models of characterization which allow the creation of taxonomy and the comparison between the images with a metric. The design space thus described will make it possible to find the non-explored areas and thus of new visualizations. Moreover, this taxonomy will confront the choices of representations, highlight the relevance of the displayed data, optimize the choices of design, and consolidate current knowledge on the relations between representations.

VI. THE CARD AND MACKINLAY MODEL

Card and Mackinlay have attempted to establish comparison criteria of the images with their work. They propose a table for each function of transformation (*Table 2*).

TABLE 2
C&M REPRESENTATION MODEL

				automatic perception						Controles perception	
Name	D	F	D'	X	Y	Z	T	R	-	[]	CP

The lines correspond to the input data. The column D and D' indicate the type of data (Nominal, Ordered, and Quantitative). F is a function or a filter which transforms or creates a subset of D. Columns X, Y, Z, T, R, -, [] are derived from the visual variables of Bertin [[1]]. The image has three and a half dimensions: X, Y, Z plus time T. R corresponds to the retinal perception which clarifies the method employed to represent information visually (color, form, size…). The bonds between the graphic entities are noted with '-', and the concept of encapsulation is symbolized by '[]'. Finally a distinction is made if the representation of the data is treated by our perceptive system in an automatic or controlled way.

TABLE 3
C&M CHARACTERIZATION LEGEND

L	Line
S	Size
f	Function
N, O, Q	Nominal, Ordered, Quantitative
Lon, Lat	Longitude, Latitude
P	Point
O	Orientation

Fig. 7 : ASTER comet

Fig. 8 : Radar comet

A. ASTER Comet

The ASTER comet (*Fig. 7*) is coded by a form positioned in (X, Y) on the screen. X screen is the distance between an aircraft and its delivery point at the end of the sector, and Y screen codes the flight level. The size of comet is a function of the ground speed. The vertical speed is coded by the orientation of the comet. Table 4 describes, with the model of C&M, the main graphical transformation of the data set to the ASTER comet.

TABLE 4
ASTER COMET CHARACTERIZATION

Name	D	F	D'	X	Y	Z	T	R	-	[]	CP
Plot	Lat Lon (QxQ)	f	Q	P				Shape			
Afl	Q	f	Q		P						
Vert. speed	Q	f	Q					O			
speed	Q	f	Q					S			

B. ODS Comet

The last positions of the aircraft merge by effect of Gestalt continuity [[12]], which makes a line emerge with its particular characteristics (curve, regularity of the texture formed by the points, etc). It is not possible to characterize it directly using the C&M transformation model. But we can characterize individually the shapes which build the comet (*Table 5*). With this intention, we introduce the concept of current time (Tcur: the time when the image is displayed). The size of the square is linearly proportional to its age.

The characterization cannot integrate the result of the analysis by the controllers of the evolution of the last positions of the aircraft (speed, evolution of speed and direction). Thus, in *Fig. 8*, the shape of the comet indicates that the plane turned 90° to the right and accelerated. These data are emergent in the comet. In other words, they were not directly used to generate the image. The characterization of C&M does not make it possible to characterize this essential information for the users, and thus does not allow the comparison of different visualizations objectively. The radar comet is richer than the Aster comet; the characterization of C&M indicates the opposite. The wealth of information transmitted by each representation is thus not directly interpretable in the characterizations: the model of C&M is not adapted.

TABLE 5
C&M RADAR COMET

Name	D	F	D'	X	Y	Z	T	R	-	[]	CP
X	Q Lon	f	Q Lon	P				Shape	emerge		
Y	Q Lat	f	Q Lat		P						
T	Q	f(Tcur)	Q					S			

C. Comet comparison

The characterization of the radar speed vector (*Table 6*) shows that its size (Bertin's notation, but as it is a line, we can use the length), changes with the aircraft's speed.

TABLE 6
C&M SPEED VECTOR CHARACTERISATION

Name	D	F	D'	X	Y	Z	T	R	-	[]	CP
speed	Q	f	Q					S			
direction		f						O			

In addition, the same information is coded by the length of ASTER comet and by the speed vector of the radar's comet. The ASTER comet is thus equivalent to the radar's speed vector, modulo a translation. It is the characterization and its comparison which allows it to link two visualizations, and thus to give to the designer elements of analysis. This result shows the importance of the work carried out.

D. C&M Model conclusion

The results showed that it is possible to apply such a characterization but it is not sufficiently precise. The radar comet (*Fig. 4*) displays the last positions of the plane (increasingly small squares according to their age) clustered by the Gestalt continuity, which makes a line emerge with its particular characteristics (curve, regularity of the texture formed by the points, etc). It is not possible to characterize it directly using the model of transformation of C&M.

Moreover, it misses the metric for the comparison criteria. The interpretation of the complete characterization of an image is very complex (too many tables). It is thus advisable to extend the C&M model again, or to use a new model.

VII. PROSPECTS

The realization of this taxonomy makes it possible to consolidate current knowledge on the characterization of visualization as our knowledge on the design, perception and the relations between them. The C&M model gives some comparison items but is not accurate enough.

This article captures a state of the art in Information

Visualization. The next part of our job will be to use all those techniques to characterize ATC visualization, and to discover a common framework applicable to every display. A good trial is to find the minimum differences between views. It is easier to describe small modifications than huge changes.

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Combining Monte Carlo and Worst-case Methods for Trajectory Prediction in Air Traffic Control: a Case Study

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***Abstract* — We illustrate, through a case study, a novel combination of probabilistic Monte Carlo methods and deterministic worst-case methods to perform model-based trajectory prediction in Air Traffic Control. The objective is that of computing and updating predictions of the trajectory of an aircraft on the basis of received observations. We assume that uncertainty in computing the predictions derives from observation errors, from the action of future winds and from inexact knowledge of the mass of the aircraft. Our novel approach provides worst-case prediction sets in which the future trajectory of the aircraft is guaranteed to belong and, at the same time, an empirical distribution of the most probable trajectories which can be used to compute various estimates such as the probability of conflict and the expected time of arrival. The case study is developed using the aircraft performance model developed by the EUROCONTROL Experimental Centre in BADA (Base of Aircraft DAta).**

I. Introduction

The ability to compute a reliable prediction of the trajectory of an aircraft on a future horizon of the order of tens of minutes is an essential part of Air Traffic Control (ATC). Increasing levels of traffic both in Europe and in the US demand for more advanced trajectory prediction algorithms in order to sustain the performance of ATC - see e.g. Paglione et al. [1].

A trajectory prediction is calculated on the basis of the aircraft estimated position and state, some intent information, weather information and a performance model. The aircraft position and state can be estimated from radar measurements or can be broadcast by the aircraft itself, such as in the Mode-S [2] and ADS-B [3] systems. The intent information includes controller instructions and operational procedures (e.g. how a descent is executed). The weather information includes predicted winds and temperature profiles. The performance model describes the aircraft dynamic behavior and is essentially needed only to calculate trajectories which include a vertical displacement because commercial aircraft in level flight can be well modeled by simple kinematic models - see e.g. Paielli[4].

In a prediction on a future horizon of the order of tens of minutes there is unavoidable uncertainty. In the seminal papers of Paielli and Erzberger[5], [6], on the use of trajectory prediction to assess the probability of a future loss of safe separation between two aircraft (conflict probability), the approach to take into account uncertainty is to superimpose a distribution of position errors to a predicted nominal trajectory. The shape of the distribution of position errors is estimated on the basis of previous radar track records - see also Yang and Kuchar[7]. In Hu et al.[8] simple kinematic models driven by a stochastic wind field are used to investigate on the effect of spatial wind correlation on collision probability in level flight. Chaloulos and Lygeros[9] present a similar study based on Monte Carlo simulations of a more sophisticated wind model. The problem of estimating the probability of future conflicts and mid-air collisions has been an important benchmark for the development of advanced speed-up techniques for Monte Carlo methods – see e.g. Blom et al.[10]. Worst-case assumptions have been adopted for example in Tomlin et al.[11] for the purpose of designing safe maneuvers to resolve the encounter of a set of aircraft in level flight.

In this paper we present a case study devoted to the idea of combining Monte Carlo and worst-case methods to perform trajectory prediction. The idea of a combined worst-case and Monte Carlo methodology has been recently proposed by Balestrino et al.[12], [13]. In the case study we are concerned with the prediction of the trajectory of an aircraft on a leg of flight which includes a descent phase. The unknowns, in calculating the prediction from the point of view of ATC, are the mass of the aircraft and the action of the wind. These are realistic uncertainties in ATC[14], [15]. The purpose of the case study is to illustrate the advantages of using an aircraft performance model to calculate worst-case and probabilistic predictions at the same time. Here we adopt the aircraft performance model developed by the EUROCONTROL Experimental Centre in BADA (Base of Aircraft DAta)[16].

The paper is organized as follows. In the next section we review the Monte Carlo and worst-case approaches to estimation and prediction. In The case study we describe the design of the case study, i.e. the objective and the assumptions on the intent, the wind and the performance model. In Simulation example we illustrate the performance of our approach in different simulation scenarios. In the last section we state our findings and conclude the paper.

The solution of the case study has entailed the development of tailored algorithms to implement our approach within the full non-linear performance model developed in BADA [16].

A detailed technical presentation of the algorithms goes beyond the scope of this paper; a longer technical report is available upon request.

II. THE METHODS

In the stochastic Monte Carlo approach an empirical distribution of trajectory predictions is constructed by drawing random samples from Bayesian prior distributions on the initial state and on the unknowns (in our case the mass of the aircraft and the wind). The aim is to approximate the a posteriori distribution of the future trajectory given the priors on the unknowns and given the observations and the likelihood of observation errors. The approach extends the applicability of the popular Kalman filtering techniques to general non-Gaussian and non-linear models. On-line applications, such as trajectory prediction, require a computationally efficient implementation usually denoted sequential Monte Carlo or particle filtering - see e.g. Blom et al.[10], Van der Merwe et al.[17], Doucet et al.[18], Arulampalam et al.[19]. In particle filtering, the sampled predictions are computed sequentially on the basis of the last received observation without the need to reprocess older observations each time a new observation is received. The appeal of a Monte Carlo approach stems from the fact that it can be used in very complex problems and, in general, is straightforward to implement since it simply requires to run simulations of the model. The sampled trajectory predictions obtained in the Monte Carlo approach can be used to compute various estimates such as the probability of conflict with another aircraft and the expected time of arrival.

In the worst-case approach the aim is to compute guaranteed predictions in the form of sets containing all the trajectories which are consistent with the datum that the initial state, the unknowns and the observation errors belong to some given bounded uncertainty sets. In the context of estimation and filtering for dynamical systems this methodology is also referred to as the set-membership approach - see e.g. Bertsekas and Rhodes [20], Polyak et al.[21]. In the set-membership approach the prediction set is updated recursively. The initial predictions are only consistent with the given uncertainty sets of the initial state and of the unknowns; which are defined by existing knowledge on the model. In our case, the mass of the aircraft is known to be confined between a known minimum and a known maximum and it can be assumed that errors on the predicted winds respect to some credible bounds estimated from archived weather reports. The uncertainty sets are updated each time a new observation is received by excluding values of the unknowns which give rise to predictions which are not consistent with the received observation. Each time the uncertainty set of the unknowns is updated, a new set of guaranteed predictions is computed accordingly. The attractive feature of this approach is that the uncertainty set of the unknowns and the set of predictions are systematically reduced at the reception of each new observation while remaining guaranteed uncertainty sets in the worst-case sense.

The idea of combining Monte Carlo and set-membership methods has been proposed by Balestrino et al.[12], [13] as a novel solution to the problem of choosing representative values from the uncertainty set provided by a set-membership approach. The problem of choosing representative values is an important one because such values allow one to calculate useful quantities which can be used as 'indicative' estimates within the worst-case bounds. In the previous literature, this problem has been tackled with a deterministic approach consisting in the choice of nominal values corresponding to some geometrical definition of a center of the uncertainty set - see e.g. Bai et al.[22]. Balestrino et al.[12], [13] proposed instead the use of particle filters to construct an approximate a posteriori Bayesian distribution over the worst-case uncertainty sets. In this way one can use representative probabilistic estimates, such as the probability of conflict and the expected time of arrival, within the worst-case bounds. Balestrino et al.[12], [13] put forward this idea by developing combined Monte Carlo and set-membership algorithms for the case of a linear model. In this case study, we adopt the same general idea of combining Monte Carlo and set-membership methods but without restricting the scope to linear models because our aim is to employ the full non-linear performance model developed in BADA[16].

III. THE CASE STUDY

We consider a typical scenario in a Terminal Maneuvering Area (TMA) sector - see e.g. Lecchini-Visintini et al.[23]. In a TMA sector, aircraft, towards the end of their flight, descend from cruising altitude, around 30000 ft and above, to the entry points of the Approach Sector of the destination airport, which are typically between 5000 ft and 15000 ft. In our study, we specifically address the problem of performing trajectory prediction for an aircraft on a leg of flight composed by the following three phases: an initial phase in level flight at 30000 ft, followed by a descent to 10000ft and a final phase again in level flight at 10000ft.

The intent of the aircraft and the uncertainty affecting its trajectory from the point of view of ATC are illustrated in Figure 1. The intent is specified as follows. The aircraft is initially at 30000 ft in straight level flight. In the coordinate system of Figure 1, which has the horizontal axis aligned to the direction of the flight, the leg of flight of interest begins at (0 nmi, 30000 ft). The Top of Descent (ToD) is set at (10 nmi, 30000 ft). The aircraft will continue to travel in straight level flight and will start the descent phase when the ToD is reached. The descent phase will be executed at controlled vertical speed, or, equivalently, at controlled Rate of Climb OR Descent (ROCD). Here it is assumed that during the descent phase the pilot will use the Vertical Navigation (VNAV) system to follow

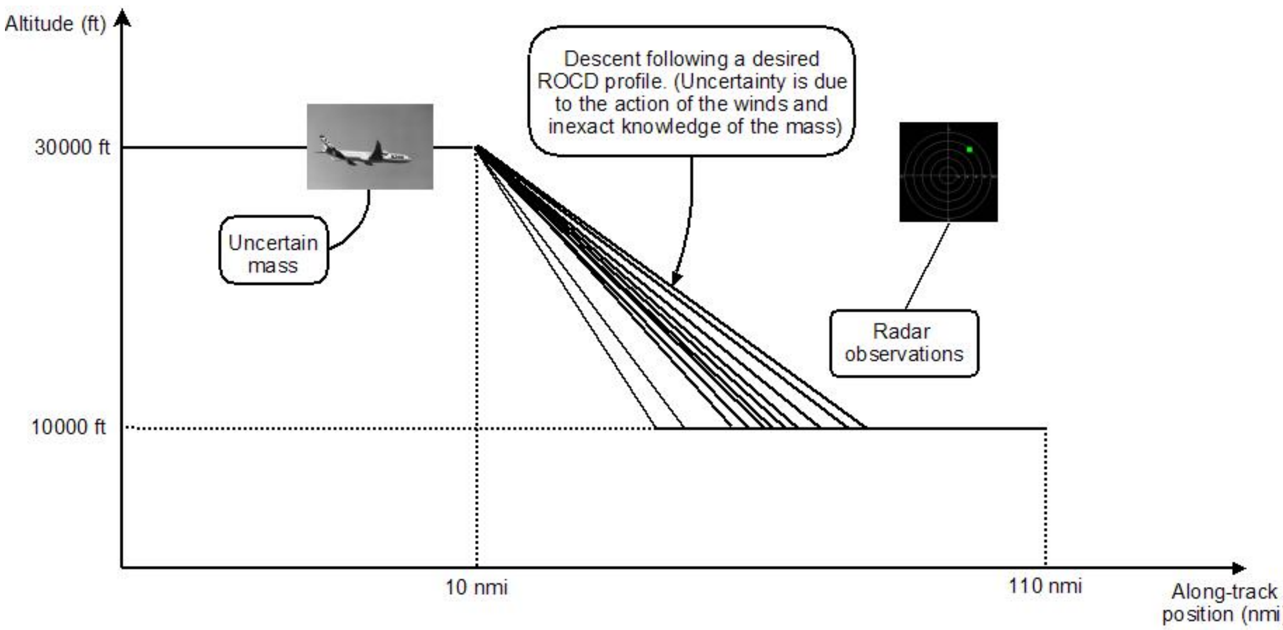

Fig. 1. A schematic representation of the flight considered in this case study.

a desired vertical path which has been issued by ATC. The aircraft will resume level flight when the altitude of 10000 ft is reached. The end of the leg of flight of interest is set at (110 nmi, 10000 ft).

We assume that the specified intent will be executed with no navigation errors. This assumption implies that: (i) the aircraft will fly on a straight route with null cross track error; (ii) the aircraft will begin the descent phase exactly when the ToD is reached; and (iii) the aircraft will execute the vertical path issued by ATC with no vertical navigation errors. From the point of view of ATC, uncertainty in the prediction of the aircraft trajectory will arise from the lack of knowledge of the exact mass of the aircraft in the prediction model, from the errors between the predicted and the actual winds encountered by the aircraft and from the observation errors. This uncertainty will affect mainly the prediction of the along track position of the aircraft, e.g. the location of the Bottom of Descent (BoD), and the Time of Arrival (TA). Our assumptions reflect the fact that current navigation systems allow the pilot to follow the ATC instructions with small errors and allow us to focus on the latter sources of uncertainty which would then be the predominant ones.

In the reminder of this section we introduce the models employed in this case study.

A. *The observation model*

We assume that radar observations are received every 6 sec and that the likelihood of observation errors has the form of a Gaussian density function with zero mean and variance σ^2= 500 m^2 truncated at 2σ. This assumption implies that each observation determines an along-track interval of length 4σ ≈ 90 m centered on the observation itself, in which the aircraft is guaranteed to be. Let us recall that the assumption that observation errors belong to a bounded set is required otherwise set-membership techniques cannot provide guaranteed predictions. Such an assumption corresponds to assume that outliers, i.e. completely wrong observations, never occur, or, if they occur, that they are detected and automatically discarded.

We assume that the aircraft airspeed is measured as well. This assumption is justified if Mode-S[2] or ADS-B[3] broadcast systems are in operation. In this case we assume that the likelihood of the air speed measurement errors has the form of a Gaussian density function with zero mean and variance σ^2=10 (m/s)^2 truncated at 2σ.

B. *The wind model*

In our case study the largest deviations from nominal predictions are caused by the action of the wind. Nominal wind predictions are usually available. However, an error in the prediction of the winds should still be taken into account in order to provide reliable trajectory predictions. A convenient choice is to consider the wind as having two components: a nominal one, which corresponds to the predicted wind, plus an additive component, which corresponds to the prediction error. We model the additive error as a zero mean random variable. Just for the sake of simplicity, we will assume that the nominal wind is zero. In our approach, a non-zero nominal component of the wind could be easily taken into account and be included in the model as a known offset to the mean of the 'stochastic wind'.

We assume that the wind remains constant at constant altitude. This assumption reflects the fact that winds at the same altitude are far more correlated than winds at different altitudes - see Cole et al. [24], Chaloulos and Lygeros [9]. In particular, this assumption can be expected to be realistic for the relatively small distances traveled in our case study. The model of the wind is based on an altitude grid consisting of 21 levels h_i^*, I = 1, .., 21 equally spaced at 1000 ft, from 10000 ft to 30000 ft. The values of the wind at these altitudes are generated as samples from a multivariate Gaussian distribution with correlation matrix which reproduce the vertical correlation of the wind. The support domain of the multivariate Gaussian distribution is truncated in such a way that the winds, and the difference between the winds at adjacent altitude levels, respect the following bounds:

$$\begin{cases} \left| w\left(h_i^*\right) \right| \le 20m/s & \forall i = 1,..,21 \\ \left| w\left(h_{i+1}^*\right) - w\left(h_i^*\right) \right| \le 20m/s & \forall i = 1,..,20 \end{cases} \quad (1)$$

(similar but less conservative bounds have been used in Kitsios and Lygeros [25]). In a similar way as it has been done before for the observation errors, these bounds are introduced in order to be able to calculate guaranteed predictions. It is important to introduce bounds also on the difference between the winds at adjacent altitude levels because the gradient of the wind has an important role in the aircraft performance model which will be introduced in the following subsection. The values of the winds at intermediate altitudes are generated by linear interpolation. A wind profile generated by our model is displayed in Figure 2. Notice that, since the wind velocity changes linearly between two adjacent levels, the gradient of the wind with respect to the altitude is piecewise constant.

The winds generated with our model are consistent with the accuracy studies performed on the database of the Rapid Update Cycle [24] performed by Schwartz et al. [26]. In their analysis the percentage of wind prediction errors greater than 10 m/s was 3 % overall, and 7 % in the worst month. Our model implies that the aircraft in level flight encounters a constant wind, and that the wind becomes instead a function of the altitude during the descent phase. More complex wind models can be easily introduced without affecting the applicability of our approach. Worst-case computations require only the values of the bounds on the winds introduced above. Monte Carlo methods require only to run many simulations of the adopted probabilistic wind model, such as the one used here, or a more complex one, such as the one used by Chaloulos and Lygeros[9].

C. The aircraft performance model

In level flight, aircraft maintain a constant airspeed which depends on the altitude. In this phase the motion of the aircraft is described well by a simple kinematic model - see e.g. Paielli [4]. Our assumption of null cross track errors simplifies the model to the following equation for the along track component:

$$x(k+1) = x(k) + v \cdot TS + w \cdot TS \quad (2)$$

where TS is the discretization step, w is the wind speed and v is the true airspeed of the aircraft. The true air speed in level flight is derived form the Calibrated Air Speed (CAS) which is a known constant parameter for each aircraft type. CAS is constant above 10000 ft until Mach transition altitude, and it can be converted into a True Air Speed (TAS) once the altitude level is known (see [16, eq (3.2-12)].). In eq [16, eq (3.2-12)] we

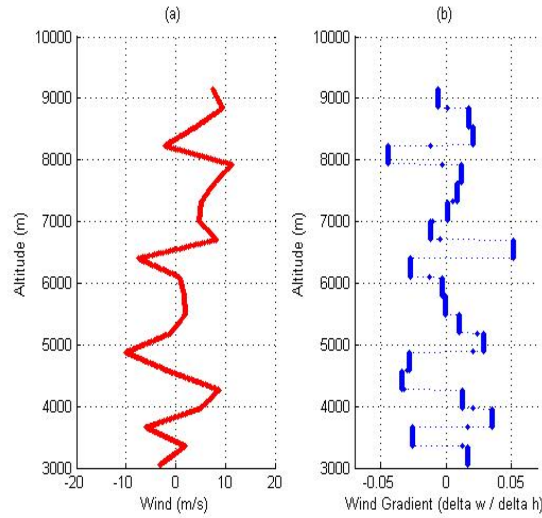

Fig. 2. (a) a possible realization of the wind profile; (b) the corresponding realization of the gradient of the wind with respect to altitude.

assumed that the pressure P_0, the temperature $Temp_0$ and the density ρ_0 at sea level are equal to their International Standard Atmosphere (ISA) values . The initial position $x(0)$ is supposed to be known within the accuracy of radar observations.

When the aircraft reaches the ToD, the model switches to a more complex one. In accordance with the BADA documentation [16], we can assume that during the descent the aircraft follows a nominal thrust profile which depends on the altitude. In addition, since we also assume that the aircraft follows a known vertical profile with no navigation errors, we actually fall under case (b) in [16, pag C7]. In this case, the ROCD, the altitude and the thrust in the BADA performance model become known at each step. Hence, the equations of the performance model can be written as:

$$\begin{cases} x(k+1) = & x(k) + v(k)\cos\gamma(k)TS + w(h(k))TS \\ h(k+1) = & h(k) + ROCD(k)TS \\ \gamma(k) = & \arcsin(ROCD(k)/v(k)) \\ v(k+1) = & v(k) + \dfrac{T(h(k)) - D(h(k),v(k),m(k))}{m(k)}TS \\ & - g \cdot \sin\gamma(k)TS - WG(h(k)) \cdot ROCD(k)\cos\gamma(k)TS \\ m(k+1) = & m(k) \end{cases} \quad (3)$$

where T is the thrust, D is the drag, g is acceleration gravity (9.81 m/s2), γ is the flight path angle and WG is the gradient of the wind with respect to the altitude. The system of equation is written emphasizing the role of the ROCD.

The descent thrust T and the drag D in (3) are computed as in (4) and (6) using correction factors and nominal values that are typical of the particular aircraft and can be found in BADA [16]. From now on, for notational convenience, $T(h(k))$ and $D(h(k),v(k),m(k))$ will be simply denoted by $T(k)$ and $D(k)$. We have:

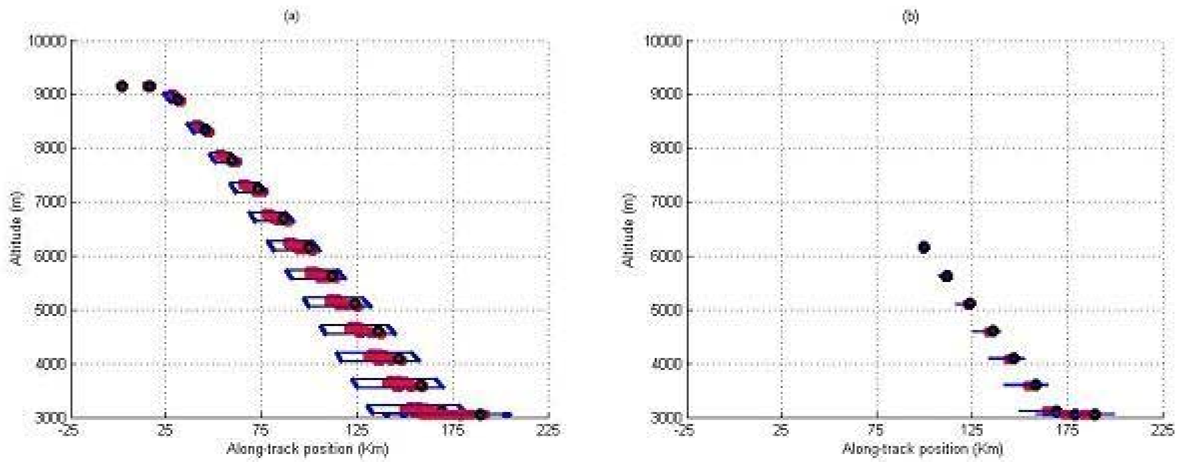

Fig. 3. Trajectory predictions drawn every 60 *sec*: (a) initial predictions; (b) half way predictions. The black circles represent the real trajectory; the red dots represent the most probable trajectories; the lines represent the guaranteed prediction

$$T(k) = C_{Tdes,high} \times T_{max\,climb}(k) \tag{4}$$

where $T_{max\,climb}(k)$ for a Jet engine type can be computed as

$$T_{max\,climb}(k) = C_{Tc1} \times \left(1 - \frac{h(k)}{C_{Tc2}} + C_{Tc3} \times h^2(k)\right) \tag{5}$$

and

$$D(k) = \frac{C_D(k) \cdot \rho(k) \cdot v^2(k) \cdot S}{2}, \tag{6}$$

where the drag coefficient $C_D(k)$ is computed as

$$C_D(k) = C_{D0,CR} + C_{D2,CR} \times (C_L(k))^2 \tag{7}$$

while the lift coefficient $C_L(k)$ is

$$C_L(k) = \frac{2 \cdot m(k) \cdot g}{\rho(k) \cdot v^2(k) \cdot S \cdot \cos\varphi(k)} \tag{8}$$

In our case, the correction for the bank angle $\varphi(k)$, in the equation of the lift coefficient, can be neglected. In the drag equation (6), $\rho(k)$ is the air density, S is the wing reference area and $v(k)$ is the true airspeed as usual. Finally, $\rho(k)$ has been computed solely as a function of the altitude of the aircraft like:

$$\rho(k) = \rho_0 \left[\frac{Temp(k)}{Temp_0}\right]^{-\frac{g}{k_T R} - 1} \tag{9}$$

where R is the real gas constant for air, $R = 287.04 m^2/(Ks^2)$, k_T is the International Standard Atmosphere (ISA) temperature gradient with altitude below the tropopause, $k_T = -0.0065 K/m$; ρ_0 and $Temp_0$ are density and temperature at sea level, here considered equal to their ISA values, $\rho_0 = \rho_{ISA} = 1.225 kg/m^3$, $Temp_0 = Temp_{ISA} = 288.15K$, and $Temp(k)$ can be computed as a function of the altitude $Temp(k) = Temp_0 - 6.5\frac{h(k)}{1000}$.

The unknown quantities in the above model are the mass *m*, the wind *w* and the gradient of the wind *WG*. We describe uncertainty on the mass through a uniform prior distribution between a maximum value and a minimum value which depend on the type of aircraft. The wind *w* and the gradient of the wind *WG* play the role of disturbances.

IV. SIMULATION EXAMPLE

In this section, we illustrate the performance of our combined worst case and Monte Carlo algorithms.

In the following simulations, the real trajectory of the aircraft is computed using randomly generated values of the unknowns and the coefficients of an A340 aircraft [16]. The actual initial position is −40 m. Each value of the unknowns has been generated according to its probabilistic model. The aircraft mass has been sampled between the minimum and the maximum values allowed for an A340 and is $2.3923 \cdot 10^5$Kg. The winds encountered during the flight are generated according to the wind model introduced in the previous section. The actual profile of the winds is the one shown in Figure 2. In the figures of this section the real position of the aircraft will be represented by black circles.

In Figure 3.(a) a trajectory prediction, made at the beginning of the flight, is displayed. In the figure, the predictions are displayed at intervals of 60 sec. The guaranteed prediction sets have a trapezoidal shape. The empirical distribution of trajectories generated by the Monte Carlo approach, which represents the most probable trajectories within the guaranteed set, is represented by red dots. Notice how the empirical distribution of the most probable trajectories is concentrated around the real trajectory and that the real

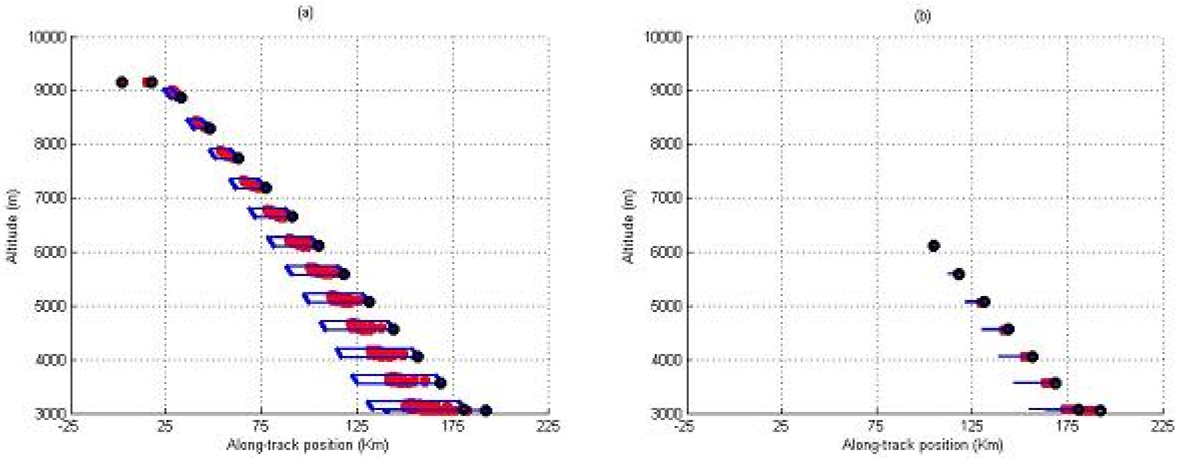

Fig. 4. Trajectory predictions in the actual worst case drawn every 60 *sec*: (a) initial predictions; (b) half way predictions. The black circles represent the real trajectory; the red dots represent the most probable trajectories; the lines represent the guaranteed prediction sets.

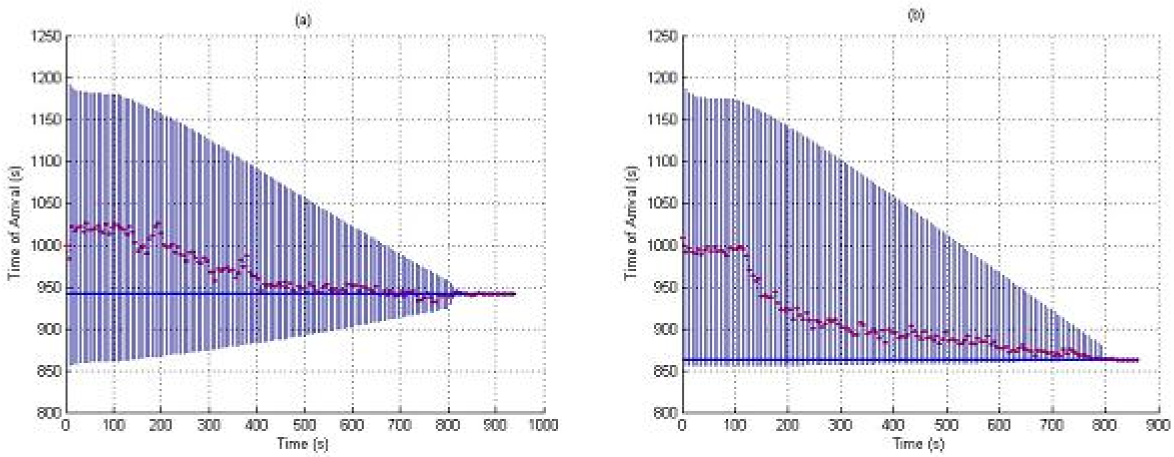

Fig. 5. Evolution of the predicted time of arrival during the flight: (a) in the case illustrated in Figure 3; (b) in the case illustrated in Figure 4. The lines represent the intervals in which the time of arrival is guaranteed to belong. The dots represent the expected time of arrival.

trajectory is always contained in the guaranteed prediction sets. In Figure 3.(b) a trajectory prediction made after the first half of the flight is displayed. In this figure, notice that the trapezoidal guaranteed predictions sets have collapsed to lines. The reason is that we assumed that the descent is executed with no vertical navigation errors. Hence, there is no uncertainty in the vertical displacement of the aircraft once the ToD has been passed. Figure 5.(a) displays the evolution of the guaranteed prediction intervals for the time of arrival, and of the expected time of arrival, during the flight.

An example where the aircraft is following a trajectory on the border of the feasible region is displayed in Figure 4. Figure 4.(a) displays again the trajectory prediction performed at the beginning of the flight, while Figure 4.(b) shows the prediction of the remaining trajectory when the aircraft has finished the first half of the flight. The reason why the aircraft is on the border of the guaranteed set is that, in this case, the mass of the aircraft and the wind profile were deliberately chosen to be at their worst admissible values. Notice that this situation is very unlikely to occur in practice, which is the reason why particles are far from the real trajectory in Figure 4.(a) and even after many measurements they still do not predict precisely the rest of the trajectory as shown in Figure 4.(b). Figure 5.(b) displays the evolution of the guaranteed prediction intervals for the time of arrival and of the expected time of arrival during this flight. Convergence to the real value is slower than in Figure 5.(a) because of the unlikely values of the uncertain quantities in this second case.

V. CONCLUSIONS

We have presented a case study devoted to the use of a combined worst-case and Monte Carlo method to perform trajectory predictions in Air Traffic Control. Each time a new observation becomes available, our algorithms provide:

- the worst-case prediction sets in which the aircraft trajectory is guaranteed to belong at each future time instant; and
- an empirical distribution which characterizes the most probable future trajectories and which can be used to compute estimates such as the expected time of arrival.

We envisage that our work will be useful to support novel conflict detection and resolution tools. An important aspect of our approach is that we have been able to employ the full non-linear aircraft performance model of BADA[16] without the need for the construction of any linearized approximate model, which is instead a common step in may other estimation and prediction methods. Future work will focus on the development of algorithms for the prediction of the trajectory during an 'open descent' when thrust and airspeed are controlled while ROCD is determined as consequence, i.e. case (a) in [16, pag C7]. In this case study we have assumed that the aircraft executes the prescribed intent with no navigation errors. Our approach does not impose any conceptual limitation to the development of prediction algorithms in which such an assumption is relaxed.

ACKNOWLEDGMENTS

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Study of Cockpit's Perspective on Human-Human Interactions to Guide Collaborative Decision Making Design in Air Traffic Management

Matthias Groppe (matthias.groppe.ext@eurocontrol.int), Marc Bui (marc.bui@laisc.net)

***Abstract*—This field research studies human-human interactions (HHI), seen from cockpit's perspective in context of Collaborative Decision Making (CDM) during flight operation situations. It is based on the assumption that cooperation among all participating operators achieves positive effect on CDM operation. The aim of the research is to identify, how factors driving cooperative behaviour are established in flight operation situations during day-to-day HHI at action level. Obtained results are used to guide future CDM design with simulation software development and system behaviour simulation. In this paper, a cockpit survey is introduced which examines two highly dynamic flight operation situations. Both situations are usually time constrained, change quickly and require synchronous human-human cooperation between pilots and multiple other operators. The first one, turn-round operation, involves HHI with information sharing via face-to-face or technological means and HHI with task/decision making distribution between pilots and other operators. The second one, the flight operation itself, involves HHI with information sharing only via technological means and HHI with task/decision making distribution between pilots and other operators.**

***Index Terms*—Air traffic management, collaborative decision making, human-human cooperation, human-human interaction**

I. Introduction

CDM was initiated as a project of working together on operational level of aircraft operators, ground handling agents, airport, air traffic control (ATC), and Central Flow Management Unit (CFMU) in order to challenge punctuality and reliability issues at increasingly congested airports. The CDM approach was introduced during field trials at selected European airports with the aim to achieve cooperation at *planning level* via information sharing and common situational awareness. However, from cockpit's perspective on current air traffic operation, many problems encountered with CDM arise from human-human interactions (HHI) at *action level*; whereby HHI at *action level* refer to interactions with a shorter time span and less abstraction than HHI at *planning level*.

Three main variable components of HHI are used to study interaction situations between pilots and other operators at action level which are *aims*, *resources*, and *abilities* of participating actors in the observed action. According Ferber [9], these variables can form different types of interaction situations which can be classified in cooperation, antagonism, and indifference. The components are used as key factors to understand HHI and to identify antagonistic or cooperative behaviour between pilots/ other operators in turn-round and flight operation situations.

In this paper, we focus on two HHI situations between pilots and other operators. The first concerns the turn-round of aircraft, where coordination of processes is necessary; processes include boarding, loading, catering, fueling, cleaning… Within this situation, cooperative HHIs are mandatory: pilots have to coordinate processes with other operators like representatives of the ground handling companies, airport, airline, air traffic control, and Central Flow Management Unit. Cooperation and decision making is distributed between pilots and other operators: Decision making for the begin of all turn-round process which are in direct relation with the aircraft (e.g. boarding, de-boarding, refueling, cleaning..), is within responsibility of the pilots: other operators are concerned with decision making for coordination and execution of these processes, and again cooperate with each other. While any delayed process start can result in an overall delay of the subsequent flight, coordination of a standard turn-round (defined as a reference model) is usually predetermined. Time span for turn-round processes is usually limited, so that any non-standard operation like aircraft change, technical repair, adverse weather operation… results in departure delay.

The second situation concerns the flight, starting from aircraft leaving the parking position until reaching parking position at destination. Coordination here is also necessary for departure and arrival sequencing with other aircraft, usage of taxiways, airways and airspace/ sectors. It is pilots' responsibility to execute the flight according defined rules under consideration of highest degree of safety possible. Other operator involved during flight for coordination of traffic is air traffic control (ATC) by keeping safe separation distance

This study is conducted with the financial support from Eurocontrol Experimental Centre.

between aircraft and managing air traffic flow by issuing clearances to the pilots. The different level of control between pilots and other operators like ATC in this situation is that ATC has authority about assigning the airspace in form of clearances to the pilots and again depend on cooperation from pilots, to adhere to these clearances. Decision making is shared between pilots and ATC within their domain relative to the situational need, but has to be executed under mentioned safety constraints. Other operators like the airline company or CFMU are only marginally involved in decision making during flight operation.

One aim is to identify how HHI are established between pilots and other operators and show cooperative behaviour during day-to-day flight operation which is assumed to be necessary in context of collaborative decision making. The other aim is to identify, if further HHI in form of negotiation has positive effect on cooperation within flight operation.

Aims	Ressources	Abilities	Type of Situation	Category
compatible	sufficient	sufficient	Independence	Indifference
compatible	sufficient	insufficient	simple working together	Indifference
compatible	insufficient	sufficient	blockade	Cooperation
compatible	insufficient	insufficient	Coordinated collaboration	Cooperation
incompatible	sufficient	sufficient	pure individual competition	Cooperation
incompatible	sufficient	insufficient	pure collective competition	Antagonism
incompatible	insufficient	sufficient	individual resource conflict	Antagonism
incompatible	insufficient	insufficient	collective resource conflict	Antagonism

Fig 1. Classification of Interaction Situations (Source: Ferber, 2001)

II. Theoretical Background

In our context of flight operation, HHI are seen as dynamic relations between pilots and other operators via a number of mutual actions. Each action by one operator has consequences which influence the behaviour of the prospective behaviour of the operators. Series of actions form events, and a number of events form the turn-round or flight situation (e.g. ATC assigns a parking position for the aircraft to the pilots (event) via mutual communication usually by two-way radio communication (HHI) in a turn-round situation). Ferber [9] defines interaction situations as *a number of behavioural patterns which evolves from a group of agents, who have to act in order to reach their targets and thereby have to regard their more or less limited resources and capabilities*. By using this definition, interaction situations can be described and analysed, because it defines abstract categories like cooperation, antagonism, and indifference via differentiation of observed key commonalities and different interaction situations. The relevant components for classification of interaction situations are the aims and intentions of the different agents, the relations of the agents to available resources, and abilities of the agents in regard to their assigned task. These criteria are used to define different types of interaction situations (*Figure 1*).

Each type of interaction situation has its own relation towards cooperation: In an *Indepence* situation, no interaction takes place and sufficient resources and abilites allow an coexistence of operators without any constraint. This situation has no relevance for ATM on congested airports. A *Simple Working Together situation* defines a collaboration situation which does not require coordination between operators, while a *Blockade, Coordinated Collaboration, Pure Individual/Collective Competition,* and *Individual/Collecitve Resource Conflict* are situations which are expected to dominate in our contemplated HHI situations. These situations require coordination between operators and, depending on resources, aims, and abilities, can result in cooperative or antagonistic behaviour.

During flight operation situations, HHI are usually not binding relations between involved actors and no mutual influence is exercised between pilots and other operators; therefore social components of the interactions are not contemplated.

Our turn-round and flight situations need sufficient operators to carry out the events, and coordination in that form which allows execution of the turn-round/ flight in a predetermined time frame. Seen from HHI perspective, the prerequisites for HHI are [9]:

- A number of actors, who are able to act and communicate.
- Situations where actors meet each other.
- Dynamic elements, which allow local, time limited relations between agents.
- A certain slack within the relation between the agents, in order to not allow only keeping, but also getting off the relation.

According Hoc [12], cooperation can exist within various levels in terms of distance from the action itself: A cognitive architecture of cooperation model classifies cooperation in abstraction level and process time depending on the proximity to the action itself (*Figure 2*).

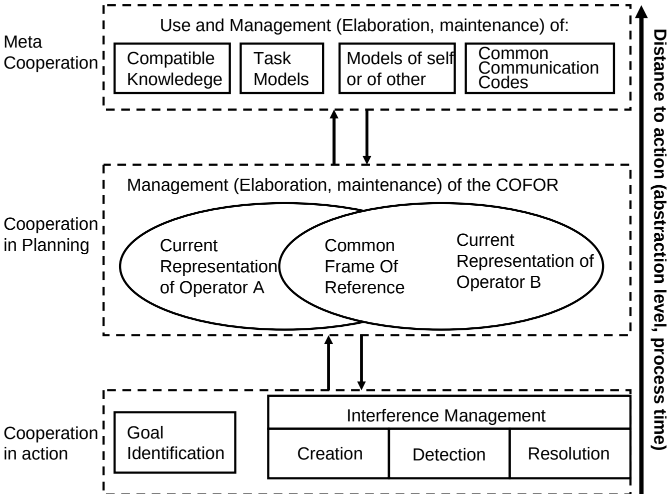

Fig 2. Processing Architecture of Cooperation (Source: Hoc 2000)

For the study of HHI situations, we focus on cooperation (or antagonism and indifference, if relevant) on action level. At *action level*, the operators perform operational activities related to their individual goals, resources, and abilities. Hoc [14] has defined four types of activities at action execution level which are interference creation (e.g. mutual control), interference detection, interference resolution, and goal identification (Goal identification also embodies identification of other operators goals). Cooperation at action level has short-term implications for the activity, as opposed to the more abstract type of cooperation at planning level. Interference creation relates to the deliberate creation of interactions; interference detection to the ability of dectecting interferences, especially in non-deliberate interference situations; and interference resolution to the actual interaction in order to find a cooperative solution. Mutual domain knowledge is the basis for other operators' goal identification, to facilitate operator's own task, the other's task, or the common task.

At *planning level*, operators work to understand the situation by generating schematic representations that are organized hierarchically and used as an activity guide [13]. Schematic representations include the concept of situation awareness [22], and operators' goals, plans, and meta-knowledge [13]; therefore current approach to CDM operation in ATM is seen as an approach towards cooperation on planning level. De Terssac and Chabaud [7] use the term COFOR (Common frame of Reference) as a mental structure playing a functional role in cooperation and as a shared representation of the situation between operators likely to improve their mutual understanding[3]. The topmost level in Hoc's model, the meta-cooperation, as a level developed from knowledge of the other two levels, is not contemplated in the study.

Also Piaget [19] distinguishes between cooperation seen from structural (e.g. network organization) or functional point of view which looks at cooperation as activities performed by individuals within a team in real time. Two minimal conditions must be met in cooperative situations: (1) Each actor strives towards goals and can interfere with other actors on goals, resources, and procedures. (2) Each actor tries to manage interference to facilitate individual activities or common task. Both conditions are not necessarily symmetric, because goal orientation or interference management depend on individual behaviour or time constraints.

Hoc [12] argues that current air traffic management (ATM) is more concerned with operators' plans, goals, or role allocation instead of common situational awareness. But Lee [16] determines situational awareness, responsibilities and control, time, workload, and safety constraints as key factors driving collaborative behaviour in air traffic control operation: *To have proper awareness of the situation, a controller and/or pilot needs to initiate or be informed of actions taken by other operators*. But time pressure and safety issues have negative effect on communicative behaviour and therefore also cooperation or common situational awareness.

Share of responsibility and control are often different but determined through situation (e.g. air traffic controllers issue clearances which have to be executed by pilots). Nevertheless, *the more assistance, the more anticipative the mode of operation in controllers and the easier the human-human cooperation* [13].

Collaborative Decision Making means *applying principles of individual decision making on groups, whereby groups are established with the aim to show collectively a specific behaviour* [15]. This implies that cooperation of participating individuals should be beneficial for CDM operation, also in air transport management. But how does cooperative work look like at day-to-day basis? Cooperation has *a wide variety of connotations in everyday usage* [23]. Do people only cooperate, if they are mutually dependant in their work or is mutual dependency sufficient for cooperation to emerge? In context of CDM operation, confrontation and combination of different perspectives of cooperation is an issue: how is pilot's perspective embedded in the current CDM approach? For Schmidt [23], the multifarious nature of the task can be matched by application of multiple perspectives on a given problem via articulation of the perspectives and transforming/ translating information of different domains.

III. Methods

A methodological approach is used to analyse interaction situations between cockpit and other actors involved for turnaround and flight situations.

First, data about the key events during turn-round and flight situations which are relevant for HHI analysis between pilots and other operators were obtained via in-depth interviews with senior commanders of different airlines. Commanders were asked to brainstorm all possible interaction situations with a check list of all events during turn-round and flight situations in order to identify pilots' perspective on HHI. All events were decomposed in elementary activities to identify cooperative, antagonistic or indifferent behaviour of the activity. One example for a typical turn-round activity is the allocation of the parking stand/gate from ATC to the pilots which is still occupied by another aircraft resulting in delay for the arriving aircraft: if information about the expected delay is forwarded to other operators including pilots before arrival (interference creation), it would allow all operators to initiate appropriate measures like reducing air speed or allocation of other stand/gate. If no information is given, the arriving aircraft has to wait at remote position with enginges running and passengers on board (as a prototypical example of a non-cooperative situation with arrival delay).

A self-administered on-line questionnaire was then developed with questions based on these HHI between pilots and other operators, using the main components of the interaction situations adapted from Ferber [9] with the aim to identify the status of the relevant components in these HHI like:

- *Compatibility and Incompatibility of aims:* Effect on cooperation can be negative, if aims are not compatible. Therefore critical activities during turn-round and flight are questioned for possible conflicting goals between pilots and other operators. Since holding of responsibility and possess of control for decision making can also be a reason for conflicting goals, pilots were also asked to assess aptitude of current state of decision making in all relevant event classes. Questions are out to test, if the decision maker in terms of responsibility and control issues is accepted by the pilots or if decision making is causing problems because of inappropriate decision maker.
- *Availability of resources*: Resources are limited, therefore conflicts can arise which result in disturbances of HHI. Increasing airport congestion and abridged turn-round time of aircraft contribute to possible shortage of resources and result in reduced latitude of action or even individual competition between operators. Questions are out to test, if resources in terms of the time available for ground processes, are aligned with the operational and safety requirements. Current approach on CDM operation is an attempt to challenge resource constraints via coordination of actions. Approaches for coordination of actions can also be used, to predict conflicts [9]. In this context, it will be analysed, how the current CDM approach is able to anticipate conflicts in order to resolve possible conflicting situations between pilots and other operators which are identified and quantified by occurrence and probability.

  In this context of main components of interaction situations, information is also seen as a *resource* which has to be available to each operator in order to execute individual task: Information has to be shared between pilots and other operators to achieve common situational awareness. Initial data from interviews relate numerous problems regarding to cooperation on failures in information sharing. A number of elementary activities/ events are used to obtain data about possible reason for failed cooperation and effects on flight punctuality caused by information sharing problems. Questions are out to test, if there is a relation between failures in information sharing and delay (departure or arrival delay). Failure is seen, if a part of information is missing or if information is not delivered on-time.
- *Ability of operators in relation to their assigned task*: It can not be assumed that knowledge and abilities of operators are automatically sufficient for executing assigned task. This is of course also appropriate for pilots, but it is unlikely to get realistic results from questioning of pilots, if the person asked has to determine or admits its' own inability. On the other hand it is unlikely that pilots are familiar with all other domains involved and can determine necessary abilities from other operators. Therefore only random questions are out to test pilots' perspective in a few events like failed information sharing or unpunctual process execution.

Overall, the questionnaire will examine, if pilot's perspective can be seen as contributing to CDM operation: This can be ascertained, if participation of pilot's information sharing and decision making can reduce current uncertainty in situational awareness and so increase flight punctuality.

Finally, semi-structured in-depth individual interviews with further representative commanders will be conducted to clarify the content of the questionnaire results. This is necessary to capture the meaning behind the essential results and to understand pilot's attitude towards cooperation.

IV. Demonstration

Data collection is still ongoing, only primary results are available to demonstrate usefulness and applicability of the survey.

A. *The Environment of the Cockpit*

Activity analysis on flight decks of commercial aircraft shows two pilots sharing flying and other duties like communication with ATC, monitoring flight instruments and all other tasks necessary. While pilot flying is responsible for steering and navigation of the aircraft, pilot not flying disburdens him with all other duties necessary in order to maximise safety by clear task sharing, since primary responsibility of the pilots is to steer the aircraft from departure to destination airport under maximum possible safety considerations.

In various situations they encounter interactions and interrelations with other actors involved in ATM operation. Flight relevant and operational information is shared with them.

The environment of the aircraft specifies a special case of decision making: the commander of the aircraft has the topmost responsibility of all decision making on board the aircraft. This can be compared as decision making with an individual decision maker and a group of advisers. He can either use his position to listen to his various advocates of different positions or actions or execute a structured analysis by the use of help from experts or advisers (airline company, ATC, ground handlers….). It is his final responsibility to identify key uncertainties in decision making and either adhere to objectives for the organisation or his personal goal. Conflicts can arise through levels of authority and responsibility between advisers and the cockpit. Further losses of efficiency in this kind of decision making may result from other players' interactions, lack of information or limited ability of decision making. The advantage from this individual decision making is that a group of advocates is involved and therefore has more resources available [20]. Decision making seen from cockpits' perspective is also distributed since a number of decisions necessary for the flight operation remain in responsibility of the advisers (ATC, airline company, airport….).

Figure 3 shows a typical flow of HHI from cockpit's perspective identified from own experience: Aims, resources, and abilities form the basis for information exchange, decision making, and possible negotiation. Information exchange again is the basis for common situational awareness and coordination among operators. Decision making anticipates information exchange among actors which can also be used for mutual's goal identification.

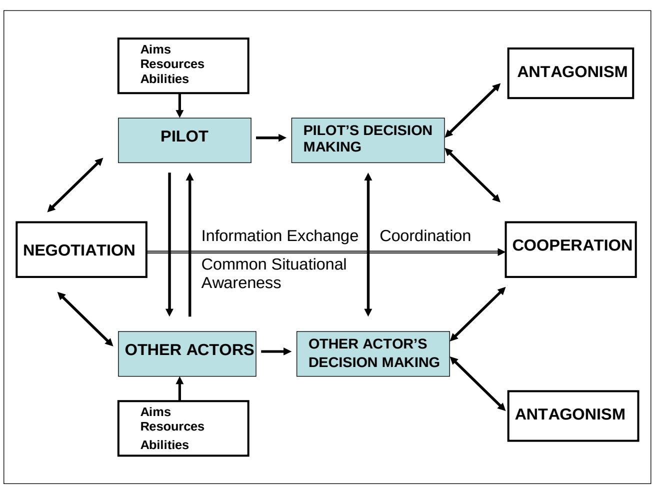

Fig 3. Cockpit's Perspective of Human-Human Interactions in ATM (Source: Own Illustration)

B. *The Collaborative Decision Making Approach in ATM*

The basic Airport CDM includes *Airport CDM Information Sharing* and the *CDM Turn-round Process* as a requirement for all subsequent airport CDM applications. Information sharing uses existing infrastructure at airports, but combines data from different sources and operators. Quality of information at each phase of flight is determined by defined rules in order to establish a common situational awareness between all operators involved.

The *Milestones Approach* defines the airport CDM turn-round process which links the flight and ground segments via a set of milestones in the aircraft turn-round process, ranging from planning of the inbound flight until the take off of the flight at the subject airport. Each milestone is monitored and allows participating operators to identify possible deviations from schedule by the use of an alarm system.

Subsequent Airport CDM levels are the *Variable Taxi Time Calculation* and the *Collaborative Management of Flight Updates (Level 2).* Variable taxi time calculation aims the introduction of a realistic taxi time in order to increase punctuality and slot adherence. Collaborative management of flight updates aims an improved operation and flexibility by slot swapping and slot shifting to take aircraft operators' preferences into account.

A *Collaborative Predeparture Sequence (Level 3)* aims to replace the present 'first come first serve' practice by consideration of aircrafts' and airport operators' requirements. [8].

C. *Identified Modes of Human-Human Interactions*

It was already discussed that human-human interactions may result in cooperation, antagonism, and indifference. Interactions will first be divided in turnaround and flight situations and then classified:

According De Ferber [9] cooperation is possible, if aims are compatible and abilities are sufficient, but resources not adequate. This would constitute the ideal case for cooperation in constrained environment like many major airports.

In ATM, HHI are embedded in HCI but HCI are not contemplated in present study.

Figure 4 provides an overview, how HCI are established in day-to-day flight operation of the two analysed flight situations.

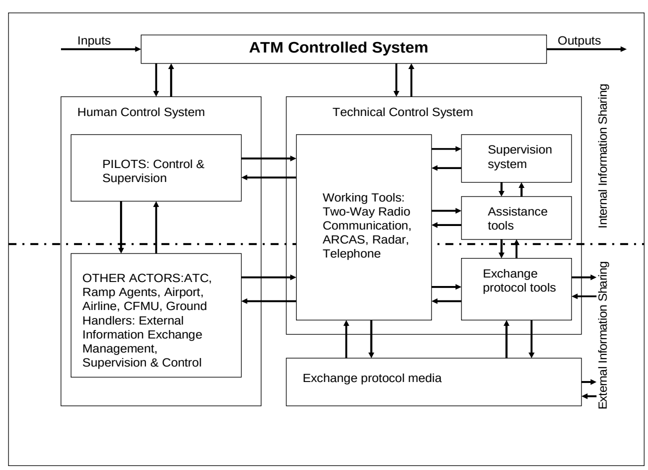

Fig 4. Information Sharing- Human-Human Interactions in combination with Human-Computer Interactions (Source: Bellorini, 1996)

D. Responsibility and control allocation between pilots and other actors

'*The allocation of functions between humans and machines is a very old topic in human engineering*' [14]. Function allocation in terms of responsibilities and control has been identified as key factor for collaborative human-human behaviour in ATM [16].

While air traffic controllers are responsible to separate the aircraft during flight, the responsibility of the pilots is the safety of the aircraft. The environment of the aircraft is a special case of interaction mode: final decision making on board of the aircraft is not shared between equitable partners, but is in the hand of the captain of the aircraft. Other actors take the role of advisers for an individual decision maker. Nevertheless all actions and decisions are obligatory on achievement of safety. The captain may either use his position to listen to his various advocates of different positions, or executes a structured analysis by the use of help from experts or advisers (airline company, air traffic control, ground handler…) It is his final responsibility to identify key uncertainties in decision making and either adhere to objectives for the organization or his personal goal.

The research shows that antagonistic or cooperative behaviour can arise through different levels of authority and responsibility between the captain and his advisers [20].

Responsibilities on ground are shared among actors: the flight manager is responsible for boarding and check-in processes, ramp agent for delivery of flight documents and other operational information. To achieve cooperation, all actors should have the same aim [14] which implies that HHI take place between *equitable* partners.

E. Modes of Information Sharing in Pilot –Other Actors Relationship

Central concern of CDM is information sharing and common situational awareness. Many studies have been devoted to information sharing at the airport control centre of CDM participating airports, but no focus has been made on exchange of information to the cockpit or receiving operational information from the cockpit.

As fare as humans are involved for information provision and creation, failures may occur and have obvious consequences on reliability [18].

Pilots were asked to identify different classes of information failures during all phases of turn-round and flight. From cockpit perspective, the main concern is, how information sharing and common situational awareness between flight crews and ground parties is accomplished in order to achieve a predictability and punctuality during flight and ground operation. It has to be addressed:

- How all necessary information is delivered to the cockpit or weather it is jammed at any interface.
- If necessary information delivered on time.
- How the information, forwarded from cockpit, is handled by other actors.
- How much delay is encountered, if information delivery is late or not executed.
- Which information not delivered has the greatest risk of producing delay.
- Which information, forwarded by crew, has greatest risk of producing delay.

F. Time Constraints

Time pressure can have opposite effect on cooperative behaviour. During peak traffic and short turnaround, pilot workload is very high for several reasons: Available time for coordination of necessary ground handling processes on ground is short or voice congestion over busy radio frequency demands high attention. Any failures in coordination or any retarded process on ground holds the risk of encountering delay. During flight on busy frequencies, issued clearances by air traffic control need to be executed promptly and often no time is left for negotiation. Especially during approach, high workload does not leave much time to gain situational awareness. Air traffic controllers' constraints are normally not visible to the pilot, but also controllers' time is very limited during busy approach hours, and therefore not much time is left, to share situational constraints or negotiate with the pilot. Especially in these situations, controllers depend on cooperation from pilots.

G. Cognitive Aspects of Human-Human Cooperation

Interactions in ATM are usually taking place among small goal oriented teams in highly dynamic situations, often limited by time constraints. Primary objective for showing cooperative behaviour for all actors are not social, but goal oriented aspects like safe and punctual transport of passengers or cargo from departure to destination. In such situations, an appropriate control mechanism for cooperative behaviour has to be established. Current approach of control mechanism uses delay code assignment: Present applied method of delay code assignment is done by individual decision of participating actor. As previously discussed, each actor strives towards own goals and it may be questioned if other actors agree to this individual decision making and how this method may be useful to enhance cooperative behaviour.

V. Conclusion

The study of general HHI in dynamic day-to-day flight operation situations can allow one to be optimistic as it regards the contribution to the CDM operation. Some initial results of the study show already that the most crucial task in HHI is a focus on cooperation with an appropriate decision making and information sharing between pilots and other operators. The application of Ferbers' types of interaction situations within the questionnaire reveals potential cooperative, antagonistic, and indifferent categories of critical flight and turn-round situations in air traffic management. The results of the questionnaire will also reveal the associated risk in terms of departure or arrival delay in minutes. This helps to identify a possible correlation of cooperation with punctuality.

In case of positive correlation between cooperation and punctuality, the results can be used to achieve more realistic flight and ground operation situations: The obtained delay information can be implemented in various ground and flight operation situation simulations to take the risk of failures in HHI during day-to-day flight operation into account.

Further research should be applied, if categories show antagonistic or indifferent behaviour between pilots and other operators' interactions. As situations show to be cooperative on action level, research can be also extended onto meta-cooperation level.

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EUROCONTROL

Information Segregation using Stereoscopic Disparity: Managing the Visual Clutter of Overlapping Labels

Stephen Peterson, Magnus Axholt and Stephen R. Ellis

***Abstract*—We present a new technique for managing visual clutter caused by overlapping labels in complex information displays. This technique, "label layering", utilizes stereoscopic disparity as a means to segregate labels in depth for increased legibility and clarity. By distributing overlapping labels in depth, we have found that selection time during a visual search task in situations with high levels of overlap is reduced by four seconds or 24%. Our data shows that the depth order of the labels must be correlated with the distance order of their corresponding objects. Since a random distribution of stereoscopic disparity in contrast impairs performance, the benefit is not solely due to the disparity-based image segregation. An algorithm using our label layering technique accordingly could be an alternative to traditional label placement algorithms that avoid label overlap at the cost of distracting motion, symbology dimming or label size reduction.**

***Index Terms*—Label placement, user interfaces, stereoscopic displays, augmented reality, air traffic control**

I. Introduction

As information systems convey more and more data in confined spaces such as computer screens, care must be taken in the user interface to manage the resulting visual clutter. In cluttered displays, information may be obscured, fragmented or ambiguous, negatively affecting system usability.

Labels, textual annotations containing object data, are one important source of visual clutter, as they overlay background layers containing their associated objects. Since legible labels need to occupy a certain minimum screen space, they may occlude or obscure other information, including other labels.

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A complete description of this work will appear in IEEE Virtual Reality 2008.

Because labels are generally associated with objects or features in the background, their placement is linked to the spatial projection of their corresponding objects on the display plane. In certain cases, such as some information visualization applications, the underlying data can be spatially or temporally rearranged to simplify labeling and data interpretation. However, in applications like see-through Augmented Reality (AR), the background normally consists of real objects directly observed by the system user; accordingly all underlying display elements cannot be adjusted freely to simplify the labeling task.

The application domain explored below is an AR display for Air Traffic Control (ATC) towers, in which tower and apron controllers operate to maintain safe aircraft separation at the airport. In our environment a Head-Up Display (HUD) system could use AR techniques to process position data and overlay controlled aircraft with labels, "data tags"", presenting vital flight information such as callsigns. This type of display could minimize controllers' head-down time and attention shifts required to scan traditional radar displays.

Despite the elevation of the control tower cab, typically about 50 meters above ground level, the lines of sight to controlled aircraft towards the local horizon are greatly compressed due to their relatively large distance from the tower, which could surpass 3 km. Therefore, the associated overlaid aircraft labels will frequently be subject to visual clutter in a HUD as they would likely overlap other aircraft and labels, especially at busy airports with distant taxiways and runways.

Traditional label placement algorithms evaluate available 2D screen space to find optimal label locations without overlap, e.g. in cartography [5, 12], scientific illustration [7] and ATC radar interfaces [5, 6, 11]. This approach to label placement is not limited to a 2D presentation medium, since it includes AR and virtual environment interfaces [2, 3, 13]. While these techniques generally avoid visual overlap, they introduce another interface design issue: which label belongs to which object? Despite the fact that a label may be connected to its background object with a line, there may be confusion as labels move according to the motion of their corresponding objects. Such confusion occurs especially if label lines intersect or are forced to overlap due to imperfect

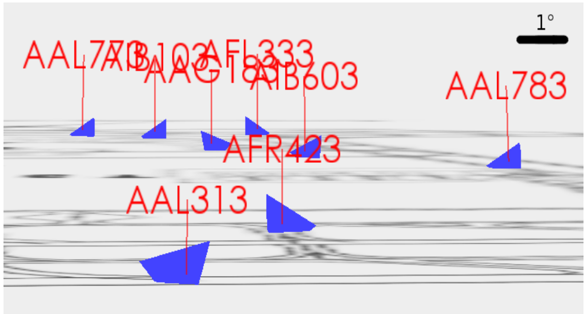

Fig. 1. A portion of a rendered scenario showing an overlap situation in the top left corner. Labels and droplines (red) were rendered on the HUD, while the aircraft objects and ground plane were rendered on the traffic display.

performance of label placement algorithms. Moreover, motion from automatic rearrangement of label positions can disturb or distract the user [1].

Other approaches aim at reducing visual clutter without spatial rearrangement, e.g. information filtering [10] or symbology dimming [8, 9] of data unimportant to the current task. However, automated importance classification and subsequent display suppression can entail a safety risk. Furthermore, declutter algorithms generally do not totally avoid the confusing overlap; they merely reduce it.

We propose an alternative approach to reduce the visual clutter associated with label overlap: *label layering*. This approach does not rearrange labels in 2D screen space, nor does it filter or dim any information. Instead it extends the design space and utilizes the depth dimension, available in e.g. stereoscopic AR displays. More specifically, our technique entails placing labels in a certain number of predetermined depth layers located between the observer and the observed objects, with droplines connecting each label to its corresponding object in depth. While the general technique of reducing visual clutter using stereoscopic disparity is not novel in itself, as discussed later on, it is to our knowledge the first application and rigorous evaluation of the technique concerning the specific problem of label placement. In this work the label layering technique is instantiated in a HUD for control towers; however, it could potentially be applied to any user interface equipped with a stereoscopic display device.

II. Method

We simulated realistic traffic at a major airport from the viewing position of an air traffic control tower. We rendered this simulation on a screen placed approximately at optical infinity (6 m) relative to the observer, a distance where optical properties of visual stimuli are similar to those at the relatively large distances in a real airport environment. We then overlaid the airport traffic with labels identifying each object, in order to evaluate whether depth segregation of overlapping labels helps declutter the display and reduce users' visual search and selection time. We rendered the overlay on a stereoscopic HUD placed 2 m from the observer, a realistic distance from the user considering a normal tower environment while minimizing the accommodation-vergence mismatch characteristic of the stereoscopic display format.

15 subjects participated in the experiment which consisted of 72 trials per subject. The task of each experimental trial was to identify and select by mouse click one aircraft in an airport traffic scenario on the traffic display, based on a given target label in the HUD. A screenshot of a rendered traffic scenario with the superimposed HUD graphics is shown in figure 1.

Three different viewing conditions were tested: i) *ordered disparity* where the depth order of the labels were correlated with the depth order of the objects, ii) *random disparity* where the depth order of the labels was randomized with respect to the depth order of the objects, and iii) *fixed disparity* where all labels were placed at a single apparent depth layer.

Moreover three different overlap levels were tested, *high*, *medium* and *low*, where two, one or zero labels respectively were fully or partially overlapping the target label.

III. Results

As the main result of this experiment, a significant effect was found using ANOVA for the interaction of *viewing condition* and *overlap level* on response time ($F(4,52) = 4.63$, $p < 0.005$), where a significantly lower response time was found for the ordered disparity condition when overlap levels were high (fig. 2). This means that ordered disparity was significantly faster (24.0%, 4.1 s) than fixed disparity ($F(2,57) = 9.72$, $p < 0.05$). Similarly it was significantly faster (37.2%, 7.6 s) than random disparity ($F(2,57) = 21.4$, $p < 0.01$).

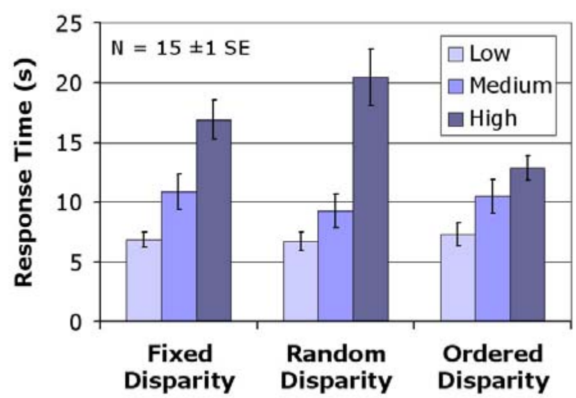

Fig. 2. Mean response time for each viewing condition, grouped by overlap level. As the main result of this experiment, an interaction effect was found in the *high* overlap level, where ordered disparity showed significantly lower response times than the other conditions.

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EUROCONTROL

User Boresighting for AR Calibration: a Preliminary Analysis

Magnus Axholt, Stephen Peterson, and Stephen R. Ellis

Abstract— **The precision with which users can maintain boresight alignment between visual targets at different depths is recorded for 24 subjects using two different boresight targets. Subjects' normal head stability is established using their Romberg coefficients. Weibull distributions are used to describe the probabilities of the magnitude of head positional errors and the three dimensional cloud of errors is displayed by orthogonal two dimensional density plots. These data will lead to an understanding of the limits of user introduced calibration error in augmented reality systems.**

I. Introduction

SPATIAL registration between computer generated and physical objects in optical see-through augmented reality (AR) requires knowledge of the precise position of the user's eyes with respect to the display surface and their head position. Because the ultimate judges of the success of the registration are the users themselves, calibration procedures generally involve some subjective alignment judgments. These judgments are boresighting tasks for which two markers at different distances are visually aligned. The alignment precision and accuracy determines the quality of the resulting system's spatial registration. Consequently, achievable registration success depends upon the precision with which users can carry out such alignments.

The boresight calibration principle has been described in early and widely referenced works. Caudell et al [2] calibrated an early AR application using boresight in terms of relative size. Janin et al. [5] described the mathematical foundations of eye-tracker transformations and noted the benefits of optimization over direct measurements. Azuma and Bishop [1] used a double boresighting technique to determine the eye-to-tracker transformation and also commented on the fact that registration accuracy depends on how successfully the user can complete the registration procedures. Tuceryan et al. [6] suggested an alternative optimization technique by which aligning screen and tracker coordinate systems reduced the number of external physical references needed for calibration.

The limits of boresight precision are related to the users' postural stability. The norms of human postural stability have been linked to the difference in stability between standing with eyes open and eyes closed. Elliott et al. [3] reports that postural stability increases by about 40% when eyes are open compared to when eyes are closed. Guerraz et al. [4] concludes that if subjects also sense motion parallax cues postural stability improves by an additional 25%.

This paper aims to establish the boresight precision and optimal recording time for AR calibration of inexperienced users. The ultimate goal is to understand the implications of postural stability as manifested by head stability for minimizing spatial registration error.

II. Boresight Experiment

The experimental apparatus consisted of an opaque screen displaying a background marker, a transparent foreground screen for a foreground maker and an ultrasound-inertia hybrid tracking device attached to the head by a strap.

A. Task

The subjects were instructed that they were going to be presented with three viewing conditions over three 30 second periods with mixed order and that their head position was going to be recorded. Audio/visual cues marked each recording period. The conditions were, 1) Eyes closed, for which subjects were instructed to simply stand, relaxed in place without moving, 2) Eyes open, for which they were to similarly stand in place but not to single out visual references to aid their stability, and 3) Boresighting for which they were to stand as in the other conditions but to keep a near and a far boresighting target visually aligned.

Two different background targets were used: a white crosshair or a highlighted spot on a background photograph. The subject's task, presented in writing, was to maintain the fore and aft targets in boresight alignment while also retaining a stable body posture.

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A complete description of this work will appear in IEEE Virtual Reality 2008.

B. *Method*

Subjects: Twenty-four voluntary subjects with normal or corrected vision participated. They were divided into two age-matched groups of 9 male and 3 female members. All were staff, contractors or students at EUROCONTROL, and were all between 27 and 59 yrs.
Experimental design: Viewing conditions were crossed with all 24 subjects for repeated measures but the two independent groups were nested within boresight background type in a mixed experimental design to provide dependent measures for analysis of variance (ANOVA).
Procedure: The subjects were instructed to assume a neutral standing pose behind a line on the floor wearing flat-soled shoes placed three centimeters apart. The position of alignment targets were adjusted so that subjects could use their dominant eye for monocular boresighting by making small, comfortable head adjustments.
Independent variables: The three viewing conditions were: Eyes closed, Eyes open, and Boresighting. The boresighting was done either with a crosshair back target or a highlighted spot on a background photograph. Each condition was repeated three times with Latin square permutations to balance sequence effects. But independent groups were used to compare the boresighting alternatives.
Dependent variables: Two dependent variables were analyzed: Sway Path and Distance from Center Point.

Sway Path is the sum of the Euclidian distances between consecutive sample points during a time period. This measurement is conventionally used to measure postural stability and can be used to confirm the normalcy of our data.

Distance from Center Point is the average unsigned distance of the head from a reference point. For our purposes of establishing boresight precision, we take the reference point to be the centroid of head position for the recording period. Knowing the mean Distance from Center Point is important because it can be related to determination of an eye position for rendering which establishes the hypothetical properties of the resulting variability of registration errors.

III. Results

Sway Path: The normalcy of the head stability data that we collected was verified by calculating the length of the path described by a subject's postural sway when eyes were open, divided by the path length when the eyes were closed. This is called the Romberg coefficient. In our case the overall value across all subjects was 0.73±0.09, right in the middle of its usual range [3].

ANOVA revealed that differences in Sway Path between the three viewing conditions were significant ($F(2,46) = 16.404$, $p <= 0.01$).

A post-hoc Scheffé test indicated that the difference between Sway Path lengths in the third repetition for eyes open and boresight viewing conditions were statistically significant ($F(2) = 36.369$, $p <= 0.01$). This indicates that the subjects' heads produce a significantly longer Sway Path when trying to boresight over two markers compared to when simply standing.

Distance from Center Point: The differences in Distance from Center Point between the three viewing conditions were also significant ($F(2,46) = 4.927$, $p <= 0.01$).

A post-hoc Scheffé test confirmed that the difference between Distances from Center Point for all repetitions for eyes open and for boresight viewing conditions were also statistically significant ($F(2) = 6.25$, $p <= 0.05$). Thus, the mean Distance from Center Point for the boresighting condition also appears greater than for the eyes open condition.

Because the Distance from Center Point can directly bear on registration error due to imperfect calibration, we have begun to study its temporal and spatial properties.

Boresight precision over time: To study subjects' alignment precision over time the 30 second recording period of the boresight viewing condition was divided into 10 three second periods for ANOVA. There was a significant effect of period ($F(9,198) = 11.593$, $p <= 0.01$). Because of the presence of outliers and asymmetric variances, the ANOVA results were confirmed with a nonparametric Friedman ANOVA ($\chi^2(9) = 46.972$, $p <= 0.01$). Also, no sequence effects could be observed for the Distance from Center Point ($F(2,44) = 0.844$, ns).

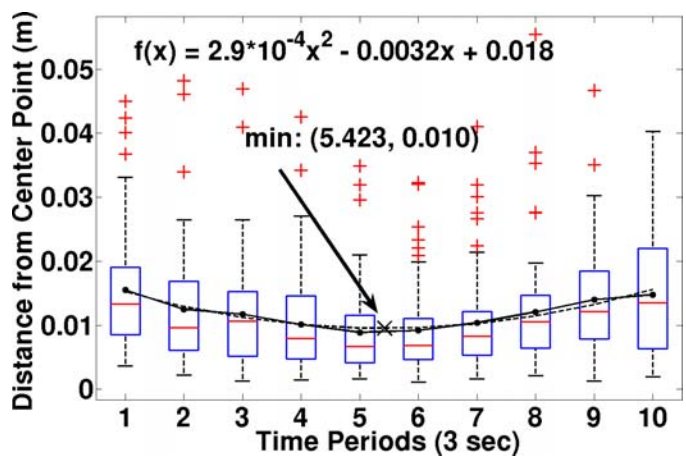

Fig. 1 Distance from center point for both boresight viewing conditions over time and its quadratic approximation.

The mean distances from each recording period describe a quadratic trend which could be used to estimate the time point at which a calibration could be determined with minimum variability (marked as X in Fig. 1). It is also evident that the gain in precision if recording between 12-15 seconds (0.009), as opposed to an immediate recording (0.015), is 6 mm.

To develop a computational model of the variation in Distance from Center Point during each period we sought a distribution function to describe this variation. The Weibull distribution seemed to have the appropriate general shape so we investigated fitting it.

Collecting all subjects' quantized position data in the 10 three sec periods resulted in 216 points for analysis. Since they appeared to distribute themselves much like a Weibull distribution ($P(x) = A * \alpha\beta^{-\alpha}x^{\alpha-1}e^{-x^{\wedge}\alpha}$), we chose to fit this distribution to our aggregated data.

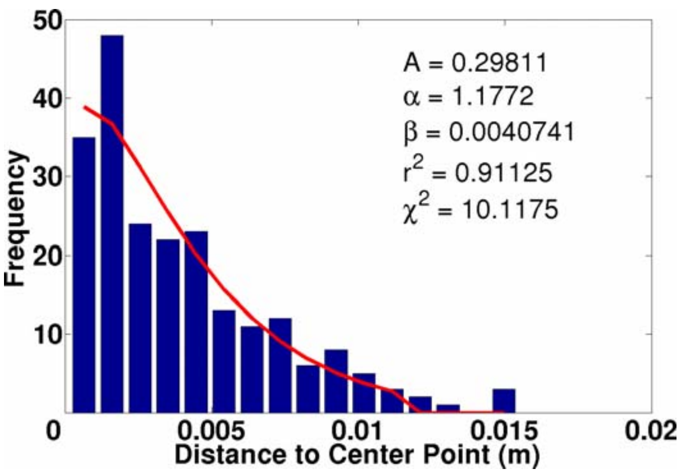

Fig. 2 Distribution of mean distances from center point in fifth period (12-15 sec) based on quantized data point for both boresight viewing conditions. The fitted distribution parameters and correlation between the fitted curve and actual frequencies are shown in the upper right.

Note that the Weibull distribution can provide a computational model for the precision of the positional aspect of boresight alignment but at least two additional parameters describing a direction in space need to be added depending upon the spatial asymmetry of the data. The parameter estimation and resulting model for calibration error is in the realm of future work.

ACKNOWLEDGMENT

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Modelling the Allocation of Visual Attention using Hierarchical Segmentation Model in the Augmented Reality Environments for Airport Control Tower

E. Pinska, C. Tijus,

***Extended Abstract*—** Augmented Reality technology allows incorporation of computer generated graphical and textual information into a real visual environment. Augmented Reality applied to the Air Traffic Control domain is expected to enhance the performance of tower controllers. However, introducing additional information to the visual scene must be conducted with care in order not to increase the clutter, saturation or complexity of the scene. Controlling the aircraft at the airport surface requires complex operational knowledge exercised under time pressure, which is considered as a complex environment. Introducing new technology to the safety critical domain like Air Traffic Control (ATC) should be carried out with special care.

We use a Hierarchical Segmentation Model (HSM), which is derived from sequentially distributed attention approach, and states that the processing of the visual scene depends on the distribution of the features and perceptual grouping in this scene. The model is based on contextual categorisation, and expressed by the mathematical formalism Galois Lattice, which provides a complexity index derived from the distribution of the attributes over objects and the categories that are used to judge or compare the complexity of the visual scenes. The model predicts the distribution of visual attention and cognitive load of the user based on the analysis of the distribution of the objects' attributes and perceptual groupings in the visual scene.

This paper presents the predictions derived from Hierarchical Segmentation Model compared to the experimental results of the eyes gaze of a novice subject scanning the controller's devices and the view out of the tower's windows. The sets of photos presenting the ground movement radar, view out of the tower's window and meteorological information display were presented to the subjects in two conditions: original and modified. The modification included adding the labels with callsigns, assigned runways number, parking places and the path indicating the movement of the aircraft.

The results of the experiment confirmed that augmenting some visual information in the scene influenced the distribution of the attention given to all the objects in the scene. The visual indices, such as labels and paths can successfully guide the subject's attention to the objects important from an operational point of view that risk to be not noticed.

The conclusions of the experiment are that the hierarchical segmentation model provides the means to evaluate the complexity of the scene. However, various possibilities of adding more visual information should be investigated with subjects that are familiar to air traffic controlling.

Index term – Airport Tower, Augmented Reality, Galois Lattice, Visual complexity

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Managing ATM Complexity: a Complex Systems Approach

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***Abstract*— In this paper we explore the effects of the structure of routes and enroute control sectors on the complexity of the congestion dynamics. This research about the relationship between dynamical complexity and structural complexity can help to understand and manage the mechanisms of saturation of the airspace.**

***Index Terms*— Complex systems, dynamical complexity, structural complexity, percolation theory, Air Traffic Management (ATM).**

I. Introduction

THE ATM system can be considered as a set of mutually interacting components in order to accomplish a certain mission or to provide a certain service. It is a complex system because of an important integration of heterogeneous sub-systems, involving not only technical but also functional and geographical issues. A local approach based analysis will not be efficient to understand the whole behavior of the system and to avoid its possible self-organized criticality. In fact, the quality of the global functioning of the system will depend on a complex combination of various sub-systems performing complicated functions. The evaluation of the impact of each function on the overall ATM system cannot be performed unless a specific approach is used.

If we consider the case of the controlled airspace congestion, the abrupt changes observed in the state of this system and its subsystems (en-route control, approach control, tower control...) have no trivial explanation and the questions that may be asked are: how do the local interactions propagate their effects to the whole system? How to evaluate the non-local interactions and time effects on the system dynamics?

As analytical solutions are very hard to determine and computationally unfeasible in the case of complex phenomena, simulation is the best way to understand the system behavior and to compute the critical parameters offering a good optimizing tool.

Percolation theory studies the deterministic propagation of a fluid on a random medium. Our purpose is to perform a holistic approach to study the airspace congestion. We provide a mathematical model based on percolation theory and taking into account the non-local interactions, representing the effects of distant control sectors on the fluidity of airspace. The non-local interactions express also, from a certain point of view, the influence of the structural properties on the dynamics of the system. The influence of time on the global behavior of the system is also considered in order to evaluate the dynamical aspect of the congestion propagation phenomenon.

II. Overview of the ATM system

The Air Traffic Management system is a complex network composed of several heterogeneous and mutually interacting subsystems. The complexity of the ATM can be related to the following factors: system size, diversity of users, safety constraints and uncertainty (weather, human factor, technical factor...). This complexity can be also related to the ATC subsystem representing the rigidly structured air space and the largely centralized, human operated control hierarchy. In fact, aircraft tend to fly along fixed corridors and at specific altitudes, depending on their route. The entire path of the aircraft is pre-planned (*flight plan*) and only minor changes are permitted on line. The ATC is in complete command of the air traffic and ultimately responsible for safety. All requests by the aircraft have to be cleared by the ATC.

Air Traffic Control (ATC), in which we observe complex phenomena, is composed of services provided by the controllers on the ground to ensure the safety and the efficiency of aircraft's motion, and are provided throughout the controlled sectors. Airspace is composed of *controlled airspace* and *uncontrolled airspace*. A controlled airspace is a set of controlled sectors, each of which being associated to a team of air traffic controllers. These air traffic controllers, are persons who operate the air traffic control system to expedite and maintain a safe and orderly flow of air traffic, and help prevent mid-air collisions. They apply separation rules to keep each aircraft apart from others in their area of responsibility and move all aircraft efficiently through "their" airspace and on to the next. [9]

Aircraft follow a planned trajectory to join two airports. They are monitored and guided throughout the whole flight time by air traffic controllers. Computers, communication links and radar screens all provide up-to-date information. Technology quite often has not one but two back-up systems to cover any possible breakdowns. The whole organization is based upon international regulations and determined routines. During the flight different services are furnished by three kinds of control activities: *Tower Control* where controllers direct aircraft that are taking off or landing at airports, *Approach Control* where controllers handle aircraft that are transitioning from the *en-route* portion of flight into the airspace around or near an airport and *En-route Control* where controllers handle aircraft that are operating on the main travel portion of their flights, typically at a high altitude.

In this work, we are especially interested in the study of the behavior of the en-route sectors because, in Europe, en-route control is the main responsible for the airline delays and traffic congestion. We include the effects of approach and tower control sectors using a non-local interaction rules.

We can consider the ATC system as a large-scale transportation control network where we look for a good porosity of the *controlled airspace* to aircraft. This *porosity* can be interpreted as the availability of the controller's services during the different phases of the flight. This porosity can be improved when the airports and non-local interactions effects are known. Our objective is to determine the effect of non-local interactions on the threshold value related to the phase transition phenomenon (abrupt change in the state of the system around a certain value of a key parameter) in order to maintain the system in a high performance state and avoid the chaotic situations. A chaotic system has the capacity to create novel and unexpected patterns of activity: it can jump instantly from one mode of behavior to another. [6]

III. THE PHASE TRANSITION PHENOMENON

The goal in this section, is to precise the complex networks phase transition property from a structural point of view using random graph theory. Then, the same phenomenon is described from a dynamical point of view through a percolation process. In fact, we can represent the controlled airspace as a set of nodes (representing the control sectors) connected to each other with edges (representing the interactions between the sectors). Within this theoretical representation we can study the structural properties of the system and their associated abrupt changes that may affect the efficiency of the dynamical processes on the network (quality of the air traffic flow). It is important to notice that theoretical properties are determined for infinite size sets using asymptotic analysis. Using simulation rules, these properties hold also for "real" systems having an important number of elements such as ATC.

A. Phase transition and random graph theory

Random Graph Theory was introduced in 1959 by Paul Erdös and Alfred Rényi to model complex networks : vertices may represent the different entities of a physical system and the edges express the relations and interactions between them. A random graph G is generated using a stochastic process called random graph model. In a random graph model, there is generally a key parameter allowing varying the average density of the graph. Formally, G(n, p) is a probability space over graphs [7] where n is the number of vertices. Given any graph theoretic property A there will be a probability that G(n, p) satisfies A, which we write P[G(n, p) |= A]. It was a central observation of Erdös and Renyi that many natural graph theoretic properties become true in a very narrow range of p.

They made the following key definition:

r(n) is called a threshold function for a graph theoretic property A if :

- when $p \ll r(n)$, $\lim_{n \to \infty} P[G(n, p) \models A] = 0$
- when $p \gg r(n)$, $\lim_{n \to \infty} P[G(n, p) \models A] = 1$

The transition observed in the first order properties of random graphs, around the threshold function is known as the zero-one law.

Structural complexity does not exist only through the phase transition phenomenon but also according to other properties. Most of "real world" networks can be considered as complex from the topological point of view. They have structural properties that do not exist in random graphs, such as a heterogeneous degree distribution, a high clustering coefficient, assortativity or disassortativity among vertices, community structure at many scales and a hierarchical structure. The two most well known examples of complex networks are those of scale-free networks and small-world networks. Both are specific models of complex networks discovered in the late 1990's by physicists.

A scale-free network is a network with a power law degree distribution ($P(k) \approx k^{-\alpha}$). These networks have no characteristic scale because of the heterogeneity of the vertices degrees: a few number of vertices called "hubs" have a high degree and the rest of the vertices have a low degree. This characteristic distribution is observed in many real world networks such as the World Wide Web, the network of Internet routers, protein interaction networks, email networks, social networks etc.

Random graphs are more adapted to model regular networks having a homogeneous degree distribution: all the nodes have almost the same degree. In fact, the degree distribution in a random graph follows a Poisson law ($P(k) \approx e^{-\langle k \rangle} \frac{\langle k \rangle^k}{k!}$).

This structural difference has an important effect on the dynamics in the network. For example, random node failures have very little effect on a scale-free network's connectivity, but deliberate attacks on the "hubs" are able to dismantle easily the whole network. In the air transportation context free-scale networks are present in different subsystems. For example, the American air transportation network has a scale-free structure.

Random graph theory deals specifically with the topological properties of networks. Concerning the dynamical aspects, percolation theory is a good framework to characterize phase transition in complex systems from a temporal point of view.

B. Percolation phase transition

Among theories using a holistic (or systemic) approach to explain the passage from the individual to the collective, from the micro to the macro, percolation theory seems to be a good theoretical framework in the ATM context: it studies the deterministic propagation of a fluid (or an information) on a random medium (or structure).

Physical problems are mathematically modeled as a network of points (or vertices) and the connections (or edges) between each two neighbors may be open (allowing the communication) with probability p, or closed with probability (1-p), and we assume they are independent. For a given p, what is the probability that an open path exists from the top to the bottom? Generally the interest concerns the behavior for large n. It is actually easier to examine infinite networks than just large ones. In this case the corresponding question is : does there exist an infinite open cluster ? That is, is there a path of connected points of infinite length "through" the network. In this case we may use Kolmogorov's zero-one law to see that, for any given p, the probability that an infinite cluster exists is either zero or one. Since this probability is increasing, there must be a critical probability p_c such that:

$$P(p)\begin{cases}=0 & if\ p<p_c\\ =1 & if\ p>p_c\end{cases}$$

where P is the percolation probability which indicates the probability of appearance of the giant cluster in the system. A model where we open and close vertices rather than edges is called site percolation while the model described above is more properly called bond percolation. The model where the uncertainty concerns both sites and bonds is called mixed percolation.

IV. TOWARDS APPLICATION OF PERCOLATION THEORY TO ATM

The complexity of controller's tasks can be attributed to the safety constraints and to the highly structured protocols. There is very limited direct communication and virtually no coordination among the aircraft. Feedback and requests from the aircraft about the plans generated by ATC are also very limited (mainly routine changes in altitude to avoid turbulence). Information is exchanged by voice, secondary radar, and autonomy is possible only in extreme situations, e.g. when Traffic Alert and Collision Avoidance System (TCAS) issue an advisory. The transition from one airspace sector to another follows a highly prescriptive set of protocols. Aircraft are constrained to enter and leave airspace sectors through entry and exit points. Passing through these points is managed by one set of air traffic controllers. When a specific sector is congested controllers can deviate the trajectory of an aircraft such that ATC services are provided by one of the contiguous sectors. This process expresses the neighborhood effects in the ATC system dynamics. In a large scale the whole system present a phase transition phenomenon [1]. It arises from the extensive feedback interactions among the densely connected sectors in local neighborhoods. In our new model we are dealing basically with en-route control sectors. We tried to include the effects of geographically distant and heterogeneous sectors (tower or approach control sectors).

We consider in the following a set of control sectors representing a finite part of the managed airspace where, as observed with empirical studies, exists a difference between the planned and realized traffic. This difference leads to the congestion of a certain number of control sectors. In order to reduce the delays and to keep a certain fluidity of the traffic, the controllers in the saturated sectors may deviate the trajectory of an aircraft to an available control sector. We should also take into account the regulation effects of the airport and the non-local (distant neighbors) sectors effects.

To be able to model these aspects, we propose to establish a bijective correspondence between the managed airspace and a square lattice (figure 1) where the neighborhood is defined using a probabilistic neighborhood function taking into account not only the geographical neighbors with immediate influence, but also a distant or time-dependent neighbors (sectors having a "delayed" effect on a specific sector).

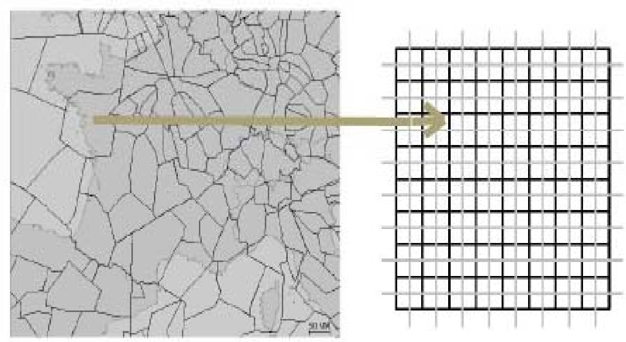

Figure 1. Correspondence between controlled sectors and sites of a square lattice.

A. The model

Let Z^2 be the plane square lattice, *p* a number satisfying $0 \le p \le 1$ and *S* the set of the vertices of Z^2 (i.e. sites or the control sectors of the studied area). Each site *s* is inactive (i.e. the sector is saturated and unable to provide more services) with probability *p* and active (i.e. the sector is available) with probability *(1-p)*. The set of inactive sites is $S = \{s \in Z^2 \mid s = inactive\}$ and the cluster composed of the sites related to the inactive site *x* is *C(x)*. Two inactive sites are related to each other if there exists a sequence of inactive sites joining between them. The cardinality of *C(x)* is noted $|C(x)|$ (for an active site $|C(x)| = \varnothing$). The distribution of $|C(x)|$ depends only on the probability of the sites inactivity. Percolation occurs if and only if $\exists x \in Z^2$ such that : $|C(x)|=\infty$

In associating each site to a control sector, we can study the *porosity* of the controlled airspace (i.e. its ability to join between two sites of the network). In the beginning, we generate at time t_0 inactive sites uniformly at random with probability *p*. Then, the structure of the system evolves at each time-step $t_{i+1}(\mathrm{i}\geq 0)$ according to the neighborhood of each site. We consider here, without loss of generality, a Moore neighborhood (eight neighbors) to express the local interactions and randomly added neighbors to express the non-local interactions. In fact, a situation where too many sites are saturated, and where the regulation (according to the estimates of the human operators) are heterogeneous, in addition to the non-local decisions (decisions token by controllers belonging to different ATC sub-systems such as approach control and en-route control), leads to the impossibility of a deterministic analytical study of the system. For these reasons, a stochastic non-local process is needed to simulate the behavior of such a system.

After a first generation of inactive sites, and at each time-step t, every site is updated simultaneously according to the following rules :

- $S(x)=\{\varepsilon_1 \ if\ C_t \ ; \ (1-\varepsilon_1) \ if \neg C_t\}$
- $R(x)=\{\varepsilon_2 \ if\ C_t \ ; \ (1-\varepsilon_2) \ if \neg C_t\}$

Where *S(x)* is the congestion function, giving the probability that an active site becomes inactive at the next step, and *R(x)* is the depression function giving the probability that an inactive site becomes active at the next step. The event

$$C_t = \sum_{k\in\Lambda(x)} a_k(t) \leq \left|\frac{\Lambda(x)}{2}\right|$$

Where $a_k(t)$ is the state of the site *k* at time *t* and C_t means that the majority of sites in the neighborhood $\Lambda(x)$ are active at time *t*. For example, in the case of a Moore neighborhood $\Lambda(x)$ =8 (excluding self connection).

In this model, local connections correspond to the interactions between geographically related sectors in the controlled airspace. In order to introduce the non-local connections, describing the far-reaching effects of distant sectors (especially tower control sectors), the mixed model known as *neuropercolation model* [6] seems to be efficient to explain the phase transition phenomenon while considering the non-local interactions effects. Starting with a lattice having only local neighborhoods, a fixed number of non-local (or remote) connections are randomly added to randomly and uniformly selected sites at each step. So, the cardinality and the configuration of the neighborhood changes over time. According to the non-locality principle, each site fate will be influenced by the sites in its direct neighborhood (Moore neighborhood) and the state of the randomly chosen non-local neighbors.

This approach allows a better understanding of the behavior of the system and the evolution of its random structure including the hidden effects of distant factors. It was shown in [1] that, according to the density of congested sites, the whole system evolves from the initial situation until its stabilization in two possible states :

- A good state, where all the delays are absorbed by the local collaborations between the contiguous control sectors.
- A bad state, where the system is trapped in a very low performance state, leading to the appearance of important delays in the whole system.

The effects of the non-local interactions introduced in this model give us a certain knowledge about the impact of these interactions on the value of the critical parameters related to the phase transition phenomenon. The simulation and the estimates of these quantitative and qualitative aspects allow a better ATM functioning optimization.

B. What can be computed to improve uncertainty and criticality management?

Simulation is an efficient tool to predict the behavior of complex systems and allows the computation of the phase transition critical parameters. The understanding of the qualitative and quantitative effects of the non-local interaction gives an interesting tool to optimize the functioning of the system and keeping it in a high performance state. After the percolation threshold, one of the important quantities in percolation theory is the probability $P_\infty(p)$ of a site to belong to the infinite (giant) cluster. In a finite size sample, $P_\infty(p)=\frac{N_p}{N_1}$, where N_p is the number of sites belonging to the giant cluster, and N_1 is the total number of inactive sites in the system. More generally:

$$\begin{cases} P_\infty(p)=0 & if\ \ p\leq p_c \\ P_\infty(p)\approx(p-p_c)^\beta & if\ \ p\geq p_c \end{cases}$$

The relation described for $p\geq p_c$ is known as the scaling law and β is called the critical exponent.

The scaling law expresses the insensibility of the characteristic quantities in a percolation process to the local and microscopic details around the critical value p_c.

It is important to study the behavior of the system around the percolation threshold p_c. The correlation length ξ defined as the mean distance between tow sites belonging to the same cluster, follows a power law when $p \rightarrow p_c$:

$$\xi(p)\approx|p-p_c|^{-\nu}$$

The value of the exponent ν is the same for $p>p_c$ and for $p<p_c$ and depends only on the lattice dimension d.

C. Simulation

The first result to notice is that the initial density of congested sites has a very low effect on the system dynamics. The most important parameters are the proportion of sites having non-local interactions and the number of remote neighbors. In fact, as we can see in figures 3 and 4, an important number of non-local neighbors (for sites having remote neighbors) have a good influence on the behavior of the system: it reduces the diffusion of the influence of congested sites to their neighbors. Concerning the effects of the proportion of sites having remote neighbors (figures 5 and 6), it is an important parameter that reduces the average number of congested sites but it has an influence on the system dynamics fluctuations: the system's density of congested sites have an important amplitude oscillation over time when this proportion is important. Concretely, the larger the number of sectors where decisions made by the controllers take into account the effects that may affect distant sectors, the more important the regulation and absorption of the congestion. A more homogeneous network, from the flight path point of view, expressing the dependence between distant sectors is better than a heterogeneous distribution (low density of sites having remote neighbors). The current topology of most controlled areas has a heterogeneous distribution (figure 2): a few number of control sectors have a high number of flights passing through them and the majority of the sectors are traversed by a small number of flights. These “hubs” have an important influence on distant sectors concerned by the flights passing through them. If they are congested and provoke delays of a certain number of aircraft, delays will propagate in the system and will affect an important number of sectors.

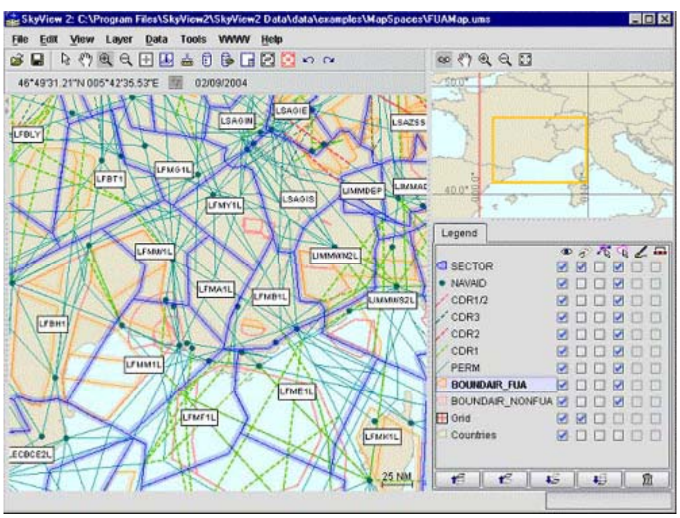

Figure 2. Scale-free aspect of the controlled area in the south of France.

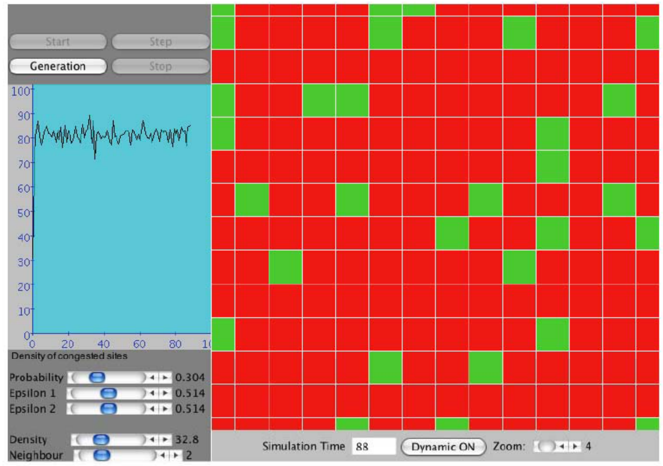

Figure 3. Congestion propagation with two remote neighbors.

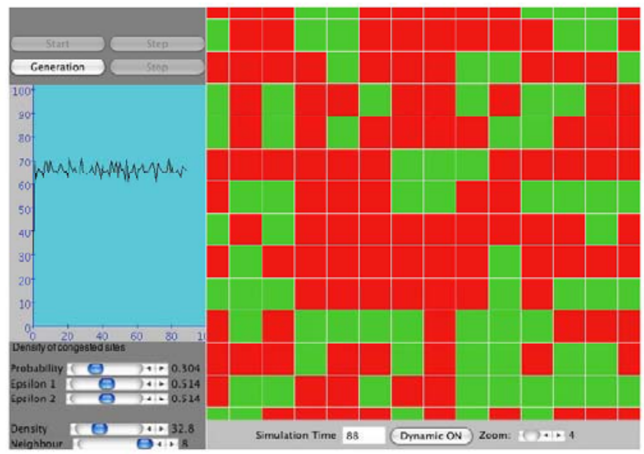

Figure 4. Reducing congestion with eight remote neighbors.

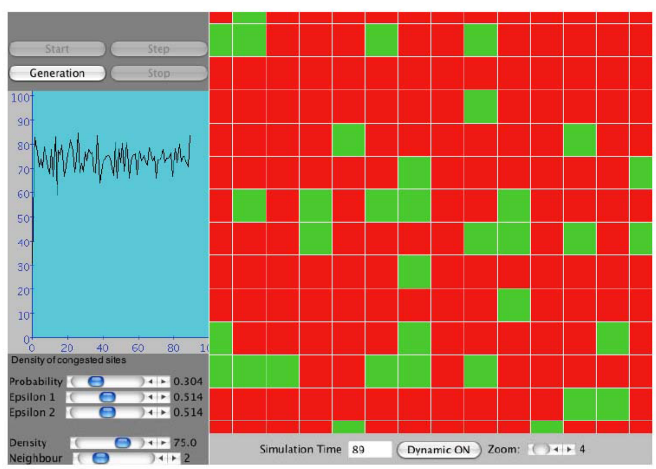

Figure 5. Reducing the average density of congested sites using an important density of sites having non-local interactions.

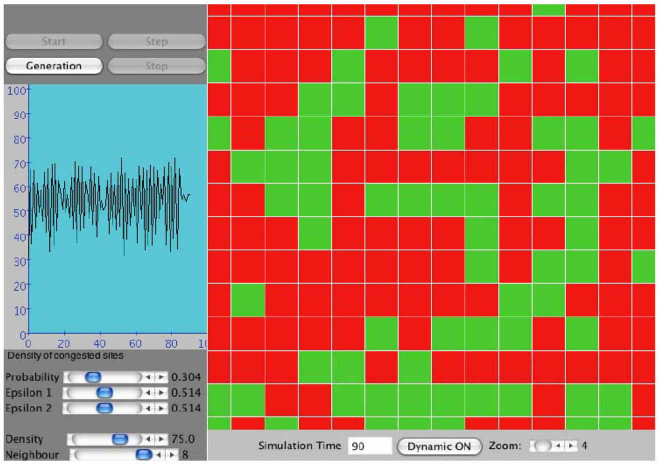

Figure 6. Even with an important density of sites with non-local interactions, the number of non-local neighbors is very important for reducing airspace congestion density : mean density is about 73 percent with 2 remote neighbors (figure 5) and about 55 percent with 8 remote neighbors.

Simulation was performed in Java. We considered in our simulation different sliders allowing varying the initial density of congested sites, the probabilities ε_1 and ε_2, the proportion of sites having non-local interactions and the number of non-local neighbors.

V. Conclusion

Our model suggests that controllers should take into account the effects of their decisions on distant sectors and not only on their immediate neighbors. Previous to the introduction of local decisions and optimizing rules in the system, controllers should have information about the state of different regions of the controlled airspace. The heterogeneity in the topology of the air transportation network should also be reduced in order to improve the efficiency of the system. The results obtained in this work are concordant with the general orientations of the solutions proposed in [8] using empirical studies and observations, in order to improve the global efficiency and to support a sustainable air transport business development. The study focuses on the co-ordination and co-operation between all actors dealing with ATM, like airports, airlines, air navigation services...

This work was an attempt to study the effects of the structure on the dynamics of the ATM systems. But this is not enough to understand the behavior of such a complex system. In particular we did not took into account the ATFM regulation effects which are online changes aiming to reduce the congestion of the airspace. In a future work we aim to conceive a more realistic and complete model including the real behavior of the sectors, aircraft and ATFM regulation using Multi-agent simulation.

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Noise Robust Speech Watermarking with Bit Synchronisation for the Aeronautical Radio

Konrad Hofbauer and Horst Hering

***Abstract*—Analogue amplitude modulation radios are used for air/ground voice communication between aircraft pilots and controllers. The identification of the aircraft, so far always transmitted verbally, could be embedded as a watermark in the speech signal and thereby prevent safety-critical misunderstandings. The first part of this paper presents an overview on this watermarking application. The second part proposes a speech watermarking algorithm that embeds data in the linear prediction residual of unvoiced narrowband speech at a rate of up to 2 kbit/s. A bit synchroniser is developed which enables the transmission over analogue channels and which reaches the optimal limit within one to two percentage points in terms of raw bit error rate. Simulations show the robustness of the method for the AWGN channel.**

I. INTRODUCTION

THE Aircraft Identification Tag (AIT) concept has been developed in order to reduce call sign ambiguity, to secure identification and to thereby enhance general safety and security in commercial aviation. AIT relies on digital speech watermarking technology to embed identifiers, such as the call sign, into the voice signal before the signal is transmitted to the ground. The embedded tag is a sort-of digital signature of the aircraft. The tag is hidden in the air-ground voice message as watermark. It is meant to be extracted on the ground and for example transformed into a visual signal on the radar screen. The goal of AIT is to visually animate the aircraft the pilot is communicating with at the time, and in doing so, increase the chances of successful identification. Possible applications of AIT are the identification of the transmitting aircraft, the uplink of an ATC identification, and secure authentication between aircraft and ATC.

II. SPEECH WATERMARKING

A watermarking algorithm for this particular AIT application faces quite different challenges compared to many other watermarking domains. This is on the one side the host signal domain being speech, and the on other side the real-time broadcast environment of ATC radio. We previously presented a speech watermarking algorithm which exploits these differences. The algorithm proposed in this paper is an extension on this work and presents a system which is capable of symbol synchronisation and watermark detection in the presence of channel noise.

The linear prediction (LP) model is an all-pole filter model and particularly well suited for speech signals as the poles can model the resonances of the vocal tract. In so-called voiced speech sounds, such as the vowels, the vocal chords open and close periodically and the excitation signal resembles a pulse train. In unvoiced speech sounds, such as the fricatives, the vocal chords are permanently open and create turbulences in the air flow and therefore a white-noise-like excitation signal for vocal tract. Our watermark algorithm is based on the principle that the excitation signal in unvoiced speech can be substituted by a data signal without perceptual distortion. With an additional watermark floor and an amplification of the excitation signal the robustness can be increased.

III. SYNCHRONISATION

Synchronisation between the watermark embedder and the watermark detector is a multi-layered problem, certainly so for an analogue radio channel. The synchronisation of the voicedunvoiced segmentation in the encoder and in the decoder can be omitted by packetizing the payload data and prepending the packets by an identification sequence. Concerning the block boundaries for the linear prediction analysis in the embedder and detector it was found that a synchronisation offset in these LP block boundaries is not an issue and does not affect the bit error rate. Data frame synchronisation is achieved by the periodical embedding of a synchronisation sequence in the digital data stream. The sequence can be detected using, among others, the simple correlation rule.

If the channel is an analogue channel, the digital clocks in the embedder and detector are in general time-variant, have a slightly different frequency, and have a different timing phase. It is therefore necessary that the detector clock synchronises itself to the incoming data sequence. We present a bit synchronisation scheme based on the spectral line method: Applying a nonlinear operation on the incoming analogue signal in the detector creates a signal with a spectral component that reflects the original sampling frequency and timing phase of the embedder. This component can be extracted with appropriate filtering and the original sampling instants estimated.

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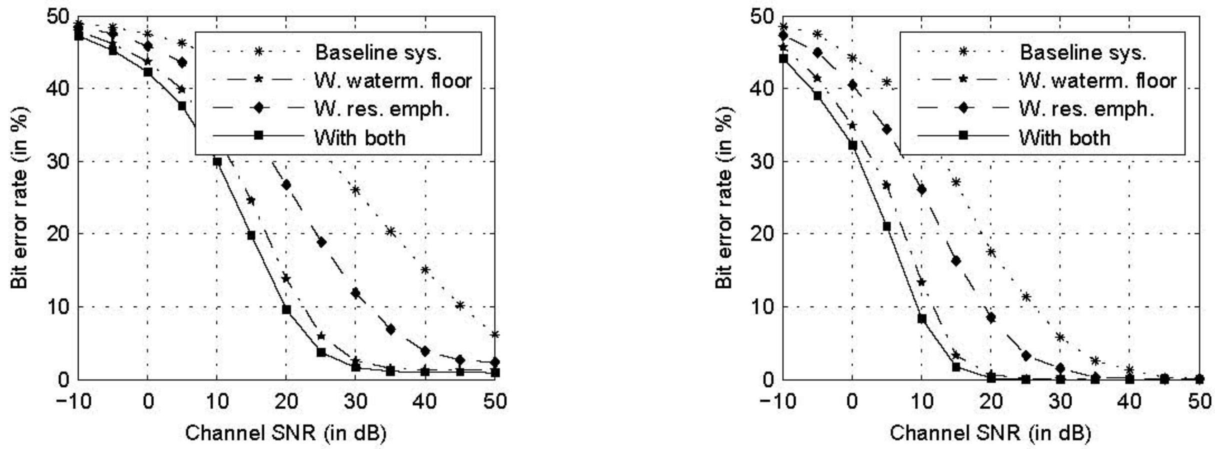

Fig 1. Raw bit error rate at different AWGN channel SNR

The bit synchronisation can be further improved by the use of an all-digital phase-locked loop (DPLL). We use a second order dual-loop structure to achieve fast locking of the loop and dynamically adapt the bandwidth of the second loop in order to increase the robustness against spurious input signals.

IV. SIMULATION RESULTS

The proposed speech watermarking system embeds in a short sequence of noisy air traffic control radio speech with a sampling rate of fs =8 kHz either 2188 bit/s of raw data or 312 bit/s with spreading for increased robustness. This rate is a variable rate which is dependent on the speech signal. Figure 1 shows the raw bit error rate for various signal-tonoise ratios (SNR) of the channel. One bit is embedded per unvoiced sample and the results are given for the cases with and without a watermark floor of gd = −20 dB and for the cases with and without a residual emphasis of ge = −20 dB. Both watermark floor and residual emphasis increase the watermark energy in the signal at the expense of perceptual quality.

The synchronisation system is shown to be able to efficiently correct timing phase offsets, sampling frequency offsets as well as jitter. Integrated in the full system, the raw bit error rate increases by less than one percentage point across all SNRs compared to hypothetical optimal synchronisation.

V. CONCLUSION

We present a speech watermarking algorithm that makes use of the specific properties of speech signals and also exploits perceptual properties of the human auditory system. We show the robustness of the system against AWGN attacks and also present a synchronisation scheme for the analogue channel that performs within a range of one percentage point of raw bit error rate compared to the theoretical optimum at simulated ideal synchronisation. By limiting ourselves to a certain type of application we are able to allow complete non-robustness to certain types of attacks but can therefore achieve exceptionally high bit rates in comparison to the available channel bandwidth. Further refinement and testing is required to make the method robust against radio channel influences that are beyond AWGN and desynchronisation.

Designing for the Resilience of Flight Approach Operations

Ronish Joyekurun, Paola Amaldi, and William Wong

Abstract—**How do we design to improve the safety of approach operations in adverse atmospheric conditions? More importantly, what are the problematic issues in the work environment which our design hypotheses need to address? This paper discusses the specificities of collaborative work on approach. Previous results are presented in the form of collaborative themes of work which allowed air-ground teams to be treated as a functional unit of analysis on approach. Last, we discuss observations with air-ground communications encountered in an ongoing study and raise a number of implications for improving air-ground work on approach.**

Index Terms—**Air Traffic Control, Safety, Collaborative Work, User Interfaces**

I. Introduction

THE design of tools to support the work of operators in the Air Traffic Control (ATC) work domain incurs a prior understanding and description of the work which we aim to support. Conversely, the different aspects of work which can be effectively supported depend on the availability of technological developments and the recognition of their utility, at a point in time [1]. The work practice and the tools which support it are mutually related and often co-evolve. Design practitioners bear the load of iteratively developing the working methods in the work domain and re-adapting tools to preserve or improve required performances.

This ideal view of situated tool development does not always occur in organisations. The rapid pace of technological evolution often imposes a number of artifacts as potential candidates for improving the work of operators. It is evident that the introduction of such tools within the workspace will lead to changed working strategies and performances. However, in a complex, non-linear and tightly coupled system, significant repercussion can be expected from even the smallest of changes [2]. As long as we attempt to measure isolated gains or losses in performance, the effects which the tools have generated in the system cannot be wholly appreciated.

Successfully integrating a tool within the work domain implies that performance gains are obtained where they are required by operators while minimising disruption to the rest of the system. For instance, a change to the symbology of a situation display for controllers without incurring much training but while improving information extraction could be regarded as a successful integration. The large skill and performance variety of expert operators can effectively mask inadequate designs and tools. Although usability and user acceptance exercises are aimed at uncovering specifically those design misfits, such efforts can be easily mitigated by implicit and explicit organisational pressures. For instance, the presence of a project manager in the simulation room or the knowledge of project expectations by experiment subjects is a factor which can bias validation outcomes. Therefore, successful tool integration is a responsibility shared by entities at all levels of an organisation.

In the rest of this paper, we focus on the work practice of air traffic control operators during the approach flight phase as a means of designing and integrating tools to support the future performance requirements of their work. A preliminary study of the collaborative interactions among air and ground teams in approach control has guided us towards tools for the improvement of their co-operative abilities [3]. We first expose the theoretical findings from literature concerning the characteristics of distributed work environments with remotely located teams working in synchrony. Then, we describe how approach teams in ATC are distinct from previously studied teams in the field of computer supported collaborative work (CSCW). The collaborative interactions of operators are then summarised from our previous study [3]. Finally, the implications of our findings are discussed.

II. Motives for Co-operation

Human to human co-operation in Air Traffic Management (ATM) is an instance of collaboration. In economics, co-operation is seen as a profit-making endeavour arising from individuals. The perception of one's limitations in accomplishing certain goals and the recognition that others' capacities are required can initiate co-operative interactions [4]. This gives a very individualistic view of the motives behind co-operative actions. Schmidt's modes and mechanisms of co-operation are grounded in a similar view of individualistic needs [5]. This view of co-operation presumes

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a number of reasons for the mutual dependence of people such as the, i) augmentation of their capacities, ii) differentiation and combination of specialties, iii) mutual critical assessment, and iv) the confrontation and combination of perspectives.

The co-operative aspects of entity behaviour can also be explained from the perspective of skill specialisation and division of labour [6]. In a complex system, the least number of entities needed to provide the most system functionality forms the baseline for an efficient organisation. This objective relies partly on the ability to minimise skill overlap, therefore leading to skill specialisation. However, specialised entities tend to become functionally isolated – they also need to be sufficiently integrated as a means of achieving global organisational goals. Therefore, a compromise for an optimally effective setup exists, where organisations attempt to normalise the overhead produced by added integration efforts [6].

III. Specificities of Approach Teams

Air-ground teams in approach ATM are very dynamic – controllers change shifts at different times of the day and airborne crews fly different routes depending on their own rotas. Although some regularity might be found with the same ground teams encountering the same crews on a weekly basis, this temporal pattern is limitedly generalisable – new crews, controller teams, rota changes make the air-ground teams inherently dynamic.

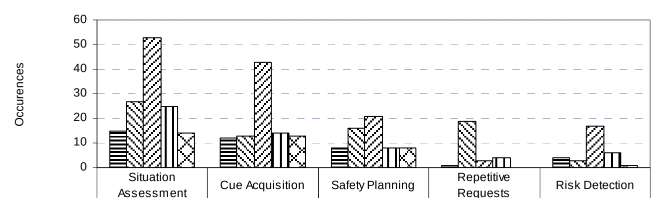
While team structures vary considerably, the functionality of approach control needs to remain stable to preserve global safety and efficiency objectives. Such stability can be influenced by factors within the operators' immediate environment, as well as the larger, encompassing environment – these have been qualified as the 'sharp' and 'blunt' end of organisations, respectively [7]. Some examples of changes which affect operations are tool evolution in the operational setting, procedure changes and behaviour modification programmes such as regular company training [8-10]. For this reason, air-ground teams in civil aviation are to be differentiated from other more structurally stable and uniformly trained teams in alternate work domains [11].

The decision-making strategies of air-ground teams on approach are also sources of large performance variations. Approach control can vary from periods of low to high work complexities [12]. The behaviour of pilots and controllers is known to be adaptive to work demands and more specifically, to changes in plan at different phases of an approach. Cognitive biases can heavily influence the decisions of teams in those situations. For instance, studies have found that the past success rates of pilots in tackling adverse weather influences their ability to judge the safety of future approaches in similar situations [13]. In such cases, operators look for cues in their environment to confirm a decision which is already implicitly agreed among team members; hence the name, confirmation bias. Similarly, crews closer to airfields have a higher probability of attempting to land in adverse conditions than crews further away – this is a case of prospective bias [14, 15].

IV. Work on Approach: Findings

We performed a conversation analysis of the verbal interactions between pilots and controller on approach to understand the work of air-ground team. The complete methodology and results have been presented elsewhere [3]. The results are centred on the activities of airborne crews and are presented in a summarised form below.

Five (5) initial broad themes grounded in the analysis of the occurrences were identified and tabulated in Fig. 1. (i) Situation Assessment: an evaluation of the situation by any team member at a moment in time, (ii) Cue Acquisition: searching and verbal confirmation of perceptual cues in the environment, (iii) Safety Planning: anticipating risky conditions and planning forth, either due to prescribed procedures or as a reaction to situation assessment, (iv) Repetitive Requests: repeated verbal requests for any type of information, and (v) Risk Detection: verbal indication of a risky situation usually after assessment and normally leading to safety planning.



	Situation Assessment	Cue Acquisition	Safety Planning	Repetitive Requests	Risk Detection
N999UA	15	12	8	1	4
5N-MAS	27	13	16	19	3
N215AA	53	43	21	3	17
N497FE	25	14	8	4	6
F-GRJS	14	13	8	0	1

Fig. 1. Activity-related keyword categories. The chart indicates the number of occurrences of keywords relating to each of 5 categories. Each keyword category represents an activity taking place on approach.

More details of the activities are shown in Table I. Each of the five categories holds a number of sub-groupings which were used to qualify the verbal interactions among pilots and controllers.

TABLE I
Activity Categories of Verbal Interactions

I. *Situation Assessment* – Evaluate Traffic Geometry; Weather Information Availability and Accuracy; Crew Decision State; Boundary of Navigation Minimas.
II. *Cue Acquisition* – Corroboration of Perceived Weather Info; Acquisition of Airfield and Runway Facilities.
III. *Safety Planning* – Request for Checklist Execution; Discussion of Approach Contingencies; Frequent Instrument Monitoring.
IV. *Repetitive Request* – Repeat requests within the same exchange; Repeat request due to insufficient or erroneous information.
V. *Risk Detection* – Expedite navigation or control procedures; Uncertainty with given information.

Air-ground teams perform a wide range of activities pertaining to their environment, equipment as well each other for achieving the smaller goals which lead to global objectives of approaching the airfield and landing the aircraft. Planning forms a crucial part of performing an approach in hazardous situations – early planning allows effective contingencies to be reviewed during periods of relatively low workload and allows time to corroborate one's evaluation of situations with others'. Subsequently, risks detected early in the scenario can also be debated and even clarified from multiply cued sources, thereby providing a natural "triangulation" of information and a greater confidence in acting upon such information later.

V. Collaborative Work Themes

After further consolidation of the activity-related themes into a collaborative framework of analysis [5], four (4) final themes were obtained and are listed, with selected examples, in Table II. The collaborative themes of work are specifically targeted at structuring the human-human interactions occurring within the activities of the air-ground team. Hence, the isolated activities of individual team members are not probed anymore; instead the effects of each member's actions on the others become the centre of our analysis.

TABLE II
COLLABORATIVE WORK THEMES

I. Monitoring of Team Members' Activities	
PNF	And 672 request latest weather now.
Controller	Now it's visibility 6km it's raining on the airfield (..).
PNF	Ok, it's allright!
PF	No!No!
PNF	Understood, understood, how many octas five hundred?
PF	How many, how many octas on it?
	(5N-MAS/10050, 10099)
II. Redirecting Attention to Perceived Priorities	
Controller	united 5 85 traffic 11 o'clock 5 miles northwest bound is a cessna 7100 straight in for runway 3 0.
PNF	okay ah we'll look for him ah how many miles are we from him?
Controller	eleven to 10 o'clock and 5 miles for united 5 85. (..)
PNF	where's the cessna for united 5 85 (..)
Controller	united 5 85 the cessna traffic is ah 10 to 9 o'clock now as you're in your turn ah passing behind you no factor.
	(N999UA/5397, 5516)
III. Implicit Redistribution of Responsibilities	
PNF	I can, we'll, we'll (start) the visual. if we we can do it.
Controller	American fourteen twenty's cleared visual approach runway
	four right. if you lose it, need some help. let me know
PNF	please.
Controller	I'll stay with you as long as possible, OK?
	that's fine, I'm working everything, American fourteen twenty.
	(N215AA/14208, 14339)
IV. Explicit Assignation of Decisional Activities	
Controller	American fourteen twenty uh, you're equipment's a lot better
PF	(..). how 's the final for two two left lookin'?
PNF	what's that?
	(..), we should be able to make two two. uh, that storm is moving this way like your, radar says it is but a little bit farther off than you thought.
Controller	American fourteen twenty roger, would you just want to shoot a visual approach?
	naw.
PF	uh, at this point we can't really make it out. we're gonna
PNF	have to stay with you as long as possible.
	(N215AA/5397, 5516)

I. Monitoring of Team Members' Activities.

In Table II, the example given shows the PNF of flight 672 requesting for updated weather information from the controller. The situation within the cockpit required the crew to judge if an approach to the destination landing field was possible, given the weather conditions. After hearing the controller's weather update, the PNF is apparently verifying a number of navigation minimas and expresses contentment with the results. However, the PF seems to detect inconsistencies with the visibility minima and expresses his concern – the PNF immediately corrects the situation by performing a repeat request for the same information, about 19s after it was first provided. Air-ground teams do not work in isolation but also cannot afford to continuously keep track of each others' activities. Our results indicate that a compromise exists namely when un-anticipated conditions occur on approach.

II.Redirecting Attention to Perceived Priorities.

The instance shown in Table II addresses the redirection of co-workers' attention during approach. The controller provides priority traffic information to flight 585 and aids the crew in locating the Cessna which is inbound to the same airfield. Later, the crew initiates an update on traffic geometry in the area by requesting the position of the Cessna – the controller indicates that this traffic is not a factor for flight 585's approach. A re-direction usually result from the perception of a deviation between an individual's and the team's cognition of a situation.

III.Implicit Redistribution of Responsibilities.

In the scenario portrayed in Table II, flight 1420 attempts to expedite an arrival by performing a visual approach. However, thunderstorm clouds pose a consistent risk of rendering the visual approach impossible – hence requiring the possible planning for a standard instrument approach by both the crew and the controller. The controller, allows the crew to pursue the visual approach while implicitly asking them to contact him in case the situation changes – assumedly, the controller is managing other tasks but provides the possibility for an interruption by the crew. This implicit re-distribution temporarily levies a number of attention management and monitoring tasks from his/her.

IV.Explicit Assignation of Decisional Activities.

The last example given in Table II portrays a situation where the appropriate approach procedure seems uncertain to the controller due to the thunderstorm in the area. A specific approach pattern is not imposed by the controller but is instead discussed with the crew. The crew is also uncertain about the approach procedure to adopt and asks to remain in contact with the controller for potentially requesting for a longer, standard approach. The urgency to land due to the thunderstorm and the inability to acquire a stable visual on the runway are seen to form competing decisional motives. Assigning a decisional activity is seen to gracefully handle an uncertain situation and shift responsibility, at least temporarily to another team member.

VI. Discussions

Atmospheric and air traffic information is distributed among airborne crews and controllers respectively. A measure of information overlap exists such that pilots can use their TCAS (Traffic Collision Avoidance System) system to gain knowledge of traffic geometries; controllers at major airports are presented with weather displays. Effective co-operation is still required in the majority of hazardous approach situations due to the equipage of certain aircraft and of the availability of ground equipment at different airfields. The results obtained in the previous study indicated that the air-ground teams could be treated as a collaborative work unit for analysing hazardous approach scenarios.

Preliminary results (unpublished) from our ongoing study seem to indicate a particular tendency for airborne crews to filter much information concerning their decisional state when speaking to ground controllers. In the cases analysed, the uncertainty of the crew seemed obvious due to the conversational cues present within their verbal exchanges. However, this uncertainty is not conveyed explicitly to the controller as soon as it arises. Instead, crews respond to controller requests in a routine fashion until the situation degenerates late on approach and contingent measures are required.

The implication of such a hypothesis is that controllers are alerted of problematic situations late during approaches, when the range of alternatives is restricted and workload is relatively high. It is not clear at this point whether crews routinely handle similar levels of uncertainty on approach and adapt to those such that they do not regard them as requiring immediate co-operation with controllers. Also, the fact that crews openly discuss uncertain situations among each other while filtering out such information from controllers deserves explanation. The last implication envisaged is of organisational proportions: are current procedures regulating human air-ground communication adequate? This observation arises because the usage of standard phraseology seems to exceedingly constrain the verbal expression of a number of uncertain situations?

VII. Conclusion

We have presented an ongoing study aimed at designing collaborative work tools for aiding air-ground teams in approach in hazardous conditions. The specificities of approach teams and the divided labour strategies on approach control require the close co-operation of air and ground teams. A preliminary study indicated that air-ground teams can be treated as a unit of collaborative work. Further implications of the work on approach raise a number of issues concerning the effective sharing of atmospheric and traffic information when they can be the most effectively assimilated and acted upon during early approach stages.

Acknowledgment

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